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ASSESSMENT OF SATELLITE EARTH OBSERVATION PROGRAMS 1991

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SPACE STUDIES BOARD

ASSESSMENT OF SATELLITE EARTH OBSERVATION PROGRAMS 1991

Committee on Earth Studies
Space Studies Board
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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SPACE STUDIES BOARD

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Foreword

This report is one in a series written by the standing discipline committees of the Space Studies Board. The purpose of this new series is to assess the status of our nation's space science and applications research programs and to review the responses of the National Aeronautics and Space Administration and other relevant federal agencies to the Board's past recommendations.

It is important, periodically, to take stock of where research disciplines stand. As an advisory body to government, the Space Studies Board should regularly examine the advice it has provided in order to determine its relevance and effectiveness. As a representative of the community of individuals actively engaged in space research and its many applications, the Board has an abiding interest in evaluating the nation's accomplishments and setbacks in space.

In some cases, recurring budget problems and unexpected hardware failures have delayed or otherwise hindered the attainment of recommended objectives. In other cases, space scientists and engineers have achieved outstanding discoveries and new understanding of the Earth, the solar system, and the universe. Although the recent past has seen substantial progress in the nation's civil space program, much remains to be done.

These reports cover the areas of earth science and applications, solar system exploration (and the origins of life), solar and space physics, and space biology and medicine. Where appropriate, these reports also include the status of data management recommendations set forth in the reports of the Space Studies Board's former Committee on Data Management and Computation. The Board has chosen not to assess two major space research disciplines—astronomy and astrophysics, and microgravity research—at this time. Astronomy and astrophysics was recently surveyed in a report under the aegis of the Board on Physics and Astronomy, *The Decade of Discovery in Astronomy and Astrophysics* (National Academy Press, Washington, D.C., 1991); the Space Studies Board is currently developing a strategy for the new area of microgravity research.

On completion of the four reports, the Board will summarize the contents of each volume and produce an overview. The Space Studies Board expects to repeat this assessment process approximately every three years, not only for the general benefit of our nation's space research programs, but also to assist the Board in determining the need for updating or revising its research strategies and recommendations.

Louis J. Lanzerotti
Chairman, Space Studies Board

Contents

Summary

During the past decade, the Space Studies Board, its Committee on Earth Studies (CES), and other bodies of the National Research Council have provided the federal government with a substantial body of advice on the study of the Earth from space. Together, these documents have contained an overall strategy for science and applications using Earth observation spacecraft and have established a set of specific recommendations for implementation of the strategic advice. This report assesses the status of the nation's civil Earth observation programs in relation to this existing body of advice and provides additional advice on how to address the unfulfilled objectives and recommendations in the current scientific and programmatic context.

Specifically, the report reviews the content of the satellite Earth observation programs of the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the Landsat system operated by the Earth Observation Satellite (EOSAT) Company as of the spring of 1991. The NASA programs are within the agency's Mission to Planet Earth initiative, which includes the Earth Observing System (EOS) and its related data and information system, the Earth Probe small- and moderate-size mission line, and a number of "precursor" missions such as the Upper Atmosphere Research Satellite (UARS) and the Ocean Topography Experiment (TOPEX/Poseidon). The NOAA programs include the two meteorological satellite series, the Polar-Orbiting Operational Environmental Satellites (POES) and the Geostationary Operational Environmental Satellites (GOES). Also considered in this assessment are some of the Defense Department's operational and experimental spacecraft, including the Defense Meteorological Satellite Program (DMSP), the Global Positioning System (GPS), and the completed Geosat mission. Finally, because the U.S. programs should be viewed in the broader international context, the experimental, operational, and commercial satellite programs of other countries are also discussed briefly.

The committee has found that substantial progress has been made in recent years in the earth science programs of NASA, although many of the science objectives previously established by this and other science advisory committees have not yet been fully achieved. More importantly, a majority of past CES recommendations are expected to be addressed by the funded and planned missions and related research programs that have been proposed for this decade through the nationally and internationally coordinated U.S. Global Change Research Program (USGCRP) and Mission to Planet Earth. *The committee concludes that with the implementation of Mission to Planet Earth, together with the planned modernization of the NOAA environmental satellite programs and the continuation of vigorous research and development of remote sensing and related technologies, the United States will ensure its leadership in Earth observations from space.*

The committee has found NASA's plans for Mission to Planet Earth to be responsive to the scientific objectives and recommendations established in past NRC reports, with the exception of several shortcomings noted below and some additional ones expressed in the body of the report. *Development of the EOS-A spacecraft and instrument complement, as well as the missions currently planned under the Earth Probe line, should proceed without delay in order to achieve the recommended science objectives. The committee also supports the instrument complement under consideration for EOS-B, but recommends that NASA carefully consider the optimum platform and orbit configuration in light of all scientific requirements.*

For spaceborne studies of the atmosphere and climate, the most significant scientific objectives will be supported by the data collected by NASA and NOAA spacecraft. Substantial progress also has been made by NASA and NOAA programs in fulfilling the space-related scientific objectives for physical oceanography, cryospheric studies, studies of tectonic deformation and variations in the Earth's rotation, and certain aspects of global biology, ecology, and biogeochemical cycles. Particularly noteworthy are NASA's support of general research and analysis (R&A) programs in the earth sciences during the past decade in the absence of many flight programs, and the high-priority attention now given by that agency to data management.

Areas of scientific research where considerably less progress has been made with Earth observation spacecraft include hydrology, land-surface geology and vegetation, and the Earth's gravitational and magnetic fields. Research in the first two of these areas has been hampered largely by the high cost of obtaining data from commercially operated remote sensing systems such as Landsat. In the future, they would be further impeded by NASA's delays in flying advanced land-surface sensors such as the Synthetic Aperture Radar (SAR) and the High-Resolution Imaging Spectrometer (HIRIS) under the EOS program. *The continued development and earliest possible deployment of the HIRIS and SAR instruments would significantly improve our ability to perform process studies and research in these areas.* Exclusive reliance on sun-synchronous polar-orbiting satellites in the EOS program would also be inadequate for monitoring a number of important processes—such as the Earth's radiative balance, the formation of clouds, and biological productivity—that vary extensively throughout the diurnal cycle. Insufficient progress in the study of the Earth's gravitational and magnetic fields has been due to the lack of specific flight opportunities, despite long-standing recommendations by the scientific community to address them. Maintaining an accurate reference system based on space geodesy techniques would be useful for monitoring long-term global change indicators such as mean sea-level change.

In meeting the goals of the Mission to Planet Earth and the USGCRP, the agencies still need to complete development of a comprehensive observational strategy that preserves long-term continuity of the highest-priority measurements and makes the best use of existing resources. *In light of limited federal budgetary resources, the committee considers it important for NASA, NOAA, and their space agency partners to:*

- *Maximize observational coverage by (1) eliminating gaps in coverage of the electromagnetic spectrum through better coordination of their respective programs and (2) reducing redundancies, with the exception of those redundancies that either help maintain continuity of key measurements or that provide multiple observations of variables with significant diurnal variations.*
- *Mount a special effort to ensure the absolute calibration and intercalibration of all Earth observation instruments to the highest achievable accuracy.*
- *Formulate a backup plan to be implemented in case of an instrument failure, to help ensure continuity in long-term observations such as those planned for EOS. This strategy may consist of the generation of alternative geophysical parameters, albeit less effective ones, either from complementary EOS instruments or from sensors flying on other NASA, U.S., or foreign spacecraft.*
- *Develop a plan for the surface and in situ data-gathering technologies and programs that are needed to complement Earth observations from space. The NASA aircraft and suborbital programs should be an integral part of this plan.*
- *Continue to transfer historical data sets onto secure media and improve the maintenance of long-term data archives.*

Both the development and implementation of this comprehensive observational strategy should be done in consultation with the scientific community.

The implementation of the EOS Data and Information System (EOSDIS) and related NOAA data management initiatives is crucial to the success of future earth science and environmental research. *It is important for NASA to continue to develop existing "pathfinder" data sets in cooperation with NOAA, and to include the data sets that will be collected by the European Earth Remote-Sensing Satellite, UARS, and TOPEX/Poseidon for prototype studies in developing the EOSDIS.*

The organizational emphasis on data systems and modeling in the recent reorganization of NASA's Earth Science and Applications Division is appropriate. The loss of identity of the traditional earth science disciplines, however, raises concerns that a balanced treatment among the disciplines may be difficult to maintain. The responsibilities of the new organizational units ought to be sufficiently broad to accommodate the requisite elements of the previous discipline structure.

The status of operational and commercial applications is in a less healthy state. Although NOAA's POES program is on track and progressing in the development of next-generation spacecraft and sensors, the agency's GOES series has encountered serious difficulties. The two-satellite GOES system is currently operating with only one spacecraft, and the development of the new GOES series, which is being carried out in conjunction with NASA, is severely over budget and behind schedule.

A number of instruments developed by NASA in the past, such as the Earth Radiation Budget Experiment scanner, the Coastal Zone Color Scanner, and the Total Ozone Mapping Spectrometer, have not been adopted by NOAA for operational implementation despite the demonstrated maturity of the technology and the well-recognized need for such continuous measurements. Although NASA and NOAA have reached a tentative agreement on the designation of several EOS instruments as "pre-operational," the framework of the eventual transfer has not been worked out and the agencies have not yet agreed on the future status of the important Moderate-Resolution Imaging Spectrometer (MODIS) instrument. *Past difficulties in transferring well-tested experimental instruments to operational status underscore the imperative for the federal government to arrive at a firm and comprehensive agreement on NASA's and NOAA's responsibilities, and on funding for the eventual transfer of key EOS instruments to a long-term monitoring program.*

The transfer of the Landsat system from NOAA to the private sector in 1985 was premature and poorly executed. Significant doubts about the future of this important remote sensing asset remain, and existing policies appear to be ineffective in assuring the future continuity of Landsat observations. *The integration of the Landsat data into the research framework of the Mission to Planet Earth and USGCRP is especially important.*

Support of research and development of the applications of remote sensing data has been reduced substantially at NASA during the past decade. Although NOAA and the commercial sector have primary responsibility for operational remote sensing, *NASA has a mandate for supporting research in, and development of, broader remote sensing applications. It is important for the agency to incorporate potential applications of EOS into its planning for the program, while preserving the primacy of the EOS program's scientific goals and objectives. These activities would best be coordinated with industry and with the commercial and government applications communities.*

The text that follows expands on the issues and recommendations highlighted in this summary, and contains a number of additional suggestions for improving our nation's satellite Earth observation programs.

1

Introduction

The Committee on Earth Studies (CES—called the Committee on Earth Sciences prior to 1989) provides continuing guidance to the Space Studies Board (SSB) in the areas of earth sciences and related remote sensing applications. The scope of its scientific advice incorporates all earth science disciplines that can be addressed from space, including studies of the atmosphere, ocean, geology and geophysics, global biology and ecology, and their interactions. The committee also identifies policy issues and provides advice concerning priorities in civil and unclassified remote sensing of the Earth, with special attention given to institutional roles and relationships among the various academic, government, and private sector entities involved. As a standing committee of the SSB, the CES assists in carrying out studies, monitoring the implementation of strategies, and providing recommendations to the National Aeronautics and Space Administration (NASA) and other government agencies.

In the past, the advice of the CES was directed primarily to the earth sciences portion of the Earth Science and Applications Division (ESAD) and to the Office of Space Science and Applications (OSSA) of NASA. Although these entities within NASA continue to be the principal focus of CES advice, the committee's purview has been broadened as a result of the SSB reorganization in 1988-1989.

Specifically, the mandate to CES now includes global biology and ecology, previously addressed by the SSB Committee on Planetary Biology (CPB), and issues related to remote sensing applications, formerly a function of the Space Applications Board (SAB) of the National Research Council (NRC). Thus, the CES now advises on programs and issues important to a wider audience both within NASA—including the applications portion of

ESAD, the Life Sciences Division of OSSA, and the Office of Commercial Programs—and within other federal agencies that have significant interests in Earth observation programs, notably the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and the United States Geological Survey (USGS), as well as the interagency Committee on Earth and Environmental Sciences (CEES). The CES also maintains contacts with other interested parties in the executive and legislative branches, in private industry, and in the university research community.

The principal NRC documents reviewed by the committee for this assessment include the following: *A Strategy for Earth Science from Space in the 1980's—Part I: Solid Earth and Oceans* (SSB, 1982a); *Data Management and Computation, Volume 1: Issues and Recommendations* (SSB, 1982b); *Snow and Ice Research: An Assessment* (PRB, 1983); *A Strategy for Earth Science from Space in the 1980's and 1990's—Part II: Atmosphere and Interactions with the Solid Earth, Oceans, and Biota* (SSB, 1985); *Remote Sensing of the Earth from Space: A Program in Crisis* (SAB, 1985); *Remote Sensing of the Biosphere* (SSB, 1986); and *Strategy for Earth Explorers in Global Earth Sciences* (SSB, 1988).

The primary purpose of this report is to identify the major scientific objectives and the principal recommendations in the documents listed above, to assess NASA's progress in relation to them, and to recommend how the perceived deficiencies might be rectified. The assessment also covers the Earth observation activities of NOAA and the private sector in the context of remote sensing applications policies and programs.

Chapter 2 focuses on NASA's response to the CES science strategy (SSB 1982a, 1985) and to the principal recommendations in the Committee on Glaciology report (PRB, 1983) and the 1986 CPB report (SSB, 1986). Chapter 3 reviews the status of applications programs in relation to the 1985 SAB report and examines the most important programmatic issues in relation to all the reports mentioned above. Chapter 3 is followed by references and a list of abbreviations and acronyms. Finally, the appendix contains the guidelines for this assessment.

2

Earth Science from Space

INTRODUCTION

The two-volume report from the Committee on Earth Sciences, *A Strategy for Earth Science from Space* (SSB, 1982a, 1985—hereinafter referred to as the 1982 and 1985 SSB/CES reports), together with the Committee on Planetary Biology's *Remote Sensing of the Biosphere* (SSB, 1986—referred to as the SSB/CPB report), established a broad set of scientific objectives, formulated primarily for NASA, for the study of the Earth from space. It is important to emphasize at the outset, however, that although these reports have assisted NASA in developing its Earth observation flight programs and related research plans, the agency also receives advice in this area from other groups. Numerous other advisory reports—by several other NRC committees and internal NASA advisory bodies—have collectively produced an interrelated advisory framework covering all aspects of civil Earth observation programs and policies.

The various fields of earth and environmental sciences have progressed to the point where a unified approach—based on the view that the Earth's physical, chemical, and biological processes constitute a coupled global system—is required to understand the changes that are occurring. The realization that the requisite scientific investigations must be conducted in an interdisciplinary context has led to the conceptual definition of an "earth system science" as the proper approach for such studies. Two key objectives of earth system science are (1) to obtain a scientific understanding of the Earth as a system on a global scale, by describing how its component parts and their interactions have evolved, how they function, and how they may be expected to evolve on different time scales; and (2) to develop the capability to predict those changes that will occur in the next decade to a century, both naturally and in response to human activity. The ultimate goal is to gain a deeper understanding of the processes responsible for the evolution of the Earth as a coupled system.

Achieving these objectives will require a comprehensive observational strategy and program consisting of space-based and in situ observations on a continuous basis over extended time periods. A major enhancement in the scientific computing and modeling capabilities also will be necessary to process the voluminous data sets and to develop effective methods for projecting environmental change.

These activities are being pursued on the national level through the U.S. Global Change Research Program (USGCRP) and coordinated by the federal interagency Committee on Earth and Environmental Sciences (CEES). The USGCRP, in turn, is coordinated with a number of major international research initiatives, notably the International Geosphere-Biosphere Program (IGBP) of the International Council of Scientific Unions (ICSU), and the World Climate Research Program (WCRP), which is sponsored jointly by the World Meteorological Organization and ICSU. NASA's contribution to the USGCRP is the Mission to Planet Earth, which includes the Earth Observing System (EOS) program and its data and information system (EOSDIS), the Earth Probe line of small- to moderate-size missions, and a number of independent precursor research missions. These elements of NASA's Mission to Planet Earth are augmented significantly by the operational environmental spacecraft of the National Oceanic and Atmospheric Administration (NOAA) in polar and geostationary orbits, by the Landsat system operated on a commercial basis by the Earth Observation Satellite (EOSAT) Company, as well as by certain declassified data from operational and experimental satellites of the Department of Defense. Internationally, there are numerous experimental, operational, and commercial spacecraft already in orbit or under construction by the European Space Agency and its individual member states in western Europe, and by Canada, Japan, the Soviet Union, China, and India that can be expected to contribute to the global research and monitoring effort.

This chapter provides an assessment of these flight programs in the context of the following scientific disciplines: (1) atmospheric sciences, (2) climate studies, (3) physical oceanography, (4) cryospheric research, (5) hydrology, (6) geology, (7) geodynamics, and (8) global biology, ecology, and biogeochemical cycles. The major scientific objectives for space-based observations, as outlined in the previous SSB reports (1982a, 1985, 1986), are presented for each discipline, and the status of their implementation, as well as suggestions for their improvement, are discussed briefly.

In conducting this review, the committee found that although all three SSB reports still provide valid scientific guidance according to which NASA programs can be assessed, sufficient scientific and technological progress has been made to warrant their detailed reexamination and revision within the next few years. In particular, the previous discipline-specific advice should be reconsidered in an interdisciplinary context, consistent with the evolution of scientific research.

ATMOSPHERIC SCIENCES

The Troposphere

Science Objectives

The highest-priority objectives established by the 1985 SSB/CES report for the study of the troposphere from space are to accomplish each of the following:

1. To obtain global data sets for the internal and boundary forcing processes that maintain the atmospheric circulation. The required data sets are for (i) surface wind, atmospheric temperature and humidity, and stress over the oceans, and land and sea surface temperature; (ii) precipitation and closely related surface characteristics including soil moisture, snow and ice cover, and vegetative biomass; (iii) surface radiation and albedo, radiation at the top of the atmosphere; and (iv) cloud characteristics including type, amount, height, temperature, liquid water content, and radiative properties.
2. To obtain temporally continuous global data sets of sufficient spatial density and accuracy to determine the large-scale structure of the troposphere. The required data sets are for (i) wind, temperature, and moisture in the free atmosphere, and (ii) sea level pressure.

Current Status

The measurement of boundary forcing requires the simultaneous determination of wind stress, temperature, and humidity in the surface boundary layer; of surface boundary temperature and moisture variables; and of radiation fluxes at the surface and at the top of the atmosphere. The feasibility of satellite measurements of stress at the sea surface was clearly demonstrated with NASA's Seasat scatterometer. During the past decade, surface temperature measurements have been routinely made with the Advanced Very High Resolution Radiometer (AVHRR) on NOAA polar-orbiting meteorological spacecraft. Radiation fluxes at the top of the atmosphere have been assessed with the Earth Radiation Budget Experiment (ERBE) measurements on several NASA and NOAA satellites. In view of fundamental limitations on the achievable vertical resolution of temperature and moisture fields of passive infrared or microwave sounding, global distributions of temperature and humidity in the surface boundary layer can only be inferred from measurements made with relatively low vertical resolution that are extended with the aid of modeling. Similarly, surface radiation fluxes cannot be measured directly from space, but progress has been made in inferring these fluxes by combining satellite measurements, surface synoptic measurements, and models. In view of this dependence on modeling, there is a continuing need for in situ validation of surface energy and moisture flux parameters.

Passive microwave measurements have proven useful for inferring precipitation from space, but the quantitative reliability of these determinations remains uncertain. This is partly a result of the scale mismatch between the satellite measurements and ground-based radar and rain gauge network measurements, and partly because there is a great amount of uncertainty in all methods used to estimate precipitation distributions, especially over the sea. The vertical distribution of latent heat release due to precipitation, which is of central dynamical importance, has not yet been assessed from space. The usefulness of satellite instruments such as AVHRR for assessing snow and ice cover and relative changes in biomass has been demonstrated, but much remains to be done to advance the capability for assessing these surface properties, as well as soil moisture, from space.

Significant progress also has been made in the use of space observations to determine the properties of clouds from space. Microwave imagers such as the Scanning Multichannel Microwave Radiometer (SMMR), flown on Nimbus-7 and Seasat, and the Special Sensor Microwave Imager (SSM/I), flown on the Defense Meteorological Satellite Program (DMSP) series, have provided useful information on cloud liquid water and ice, as well as on precipitation. The ERBE program in conjunction with the International Satellite Cloud Climatology Project (ISCCP) has provided the research community with global data sets that are now being widely used for relating the properties of clouds to wind, temperature, and moisture fields, and to the radiation fluxes at the top of the atmosphere. In addition, space observations have been widely used in coordinated cloud process studies aimed at boundary layer clouds and cirrus clouds.

The global spaceborne measurements of temperature, moisture, cloud fields, and cloud drift winds that are key elements of the weather forecasting system are also essential measurements of the tropospheric structure component of the climate system. Polar orbiting and geostationary satellites play important complementary roles. The NOAA Polar-Orbiting Operational Environmental Satellite (POES) series currently has two orbiting spacecraft with AVHRRs and atmospheric sounders (TIROS Operational Vertical Sounder, TOVS). The NOAA Geostationary Operational Environmental Satellite (GOES) spacecraft carry infrared and visible imagers (Visible and Infrared Spin-Scan Radiometer, VISSR) as well as sounders (VISSR Atmospheric Sounder, VAS), which provide data at 30- to 60-minute intervals throughout the day. Because of launch and satellite system failures, NOAA has been operating only one GOES instead of the two needed to complement the Japanese GMS, European METEOSAT, and Indian INSAT geostationary satellites for global coverage. Despite significant technical difficulties, cost overruns, and delays, development of the next scheduled GOES satellite is moving forward, and NOAA is developing backup plans in the event that further problems threaten a gap in operational coverage.

Recommendations in the 1985 SSB/CES report identified surface pressure as an important atmospheric variable. Current spaceborne observational techniques do not provide direct measurements of surface pressure with meteorologically useful precision. For the foreseeable future, the global distribution of this parameter will have to be inferred from in situ measurements combined with indirect techniques, such as data assimilation and modeling techniques that utilize observations from space in a dynamically consistent way. The use of scatterometer measurements to infer surface wind distributions, and from these, surface pressure gradients, has been shown to be a particularly promising approach to this problem.

Anticipated Improvements

During the 1990s, implementation of the current plans of NASA, NOAA, and space agencies of other countries will make significant advances in several areas. In the near term, the European Space Agency's (ESA) Earth Remote-Sensing Satellite (ERS-1), scheduled for launch in the summer of 1991, and the ERS-2 and Japanese Advanced Earth Observing Satellite (ADEOS), both scheduled for launch in the mid-1990s, will carry scatterometers and will resume global measurements of stress at the sea surface. The Tropical Rainfall Measurement Mission (TRMM), a cooperative program between NASA and Japan that is currently planned for launch in 1996, will obtain radar measurements of precipitation at low and middle latitudes. NASA has also proposed that the TRMM carry an Earth radiation budget scanner, which would resume those critical radiation measurements that ended with the failure of the last ERBE scanner in 1990, as well as a visual infrared sounder and a lightning imaging sensor.

In the longer term, NASA's Earth Observing System (EOS), which is being planned in cooperation with ESA, Japan, and Canada, is expected to significantly improve the capabilities for atmospheric research from space. (For additional assessments of the EOS program by the NRC, please see the "Space Studies Board Position on the NASA Earth Observing System" [SSB, 1991] and *The U.S. Global Change Research Program: An Assessment of the FY 1991 Plans* [NRC, 1990].) Both the EOS measurement strategy and the selected EOS instruments are generally well suited for advancing atmospheric research. The instruments selected for flight on EOS-A include the Stick Scatterometer (STIKSCAT), Multifrequency Imaging Microwave Radiometer (MIMR), Atmospheric Infrared Sounder (AIRS), Advanced Microwave Sounding Unit (AMSU-A and -B), Moderate-Resolution Imaging Spectrometer (MODIS), Earth Observing Scanning Polarimeter (EOSP), and Clouds and the Earth's Radiant Energy System (CERES). These instruments will provide substantial improvements in the measurement of surface stress over the sea, of land and sea surface temperature, of cloud properties, and of vertical profiles of temperature and water vapor. Further, the synergisms among this set of sensors, collocated on the same platform, will make especially useful contributions to the inference of the global distribution of surface boundary forcing (momentum, sensible and radiative heat, and water vapor fluxes) and should also contribute strongly to our understanding of the relationships among cloud properties, surface fluxes, and atmospheric circulation. With the CERES instrument included in the EOS-A series, continuing data on the energy fluxes at the top of the atmosphere and of the relationships between clouds and top-of-the-atmosphere radiative fluxes will be obtained. The MODIS and MIMR sensors will contribute to the determination of soil moisture, snow and ice properties, and vegetation characteristics.

Several of the instruments under consideration for the EOS-B series could make important contributions to tropospheric science objectives. In particular, the Laser Atmospheric Wind Sounder (LAWS) could improve our understanding of surface-atmosphere exchange processes. The LAWS instrument was originally scheduled for launch on a Japanese satellite, but that does not now appear possible. The potential LAWS contribution of direct wind measurements would be of significant value for deducing tropospheric structure, particularly if errors as low as 1-2 m/s can be achieved. This is especially true for the tropics, where determination of global wind distribution by indirect means is notoriously difficult.

The proposed EOS SAR, which would fly as a separate mission, could make important contributions to the determination of the properties of sea ice and snow, soil moisture and surface water distribution on land, and vegetative structure, all of which interact in significant ways with the troposphere.

Additional Needs

The AVHRR instrument on the NOAA polar orbiters, and the VAS and VISSR instruments on the NOAA GOES are providing important historical data sets for future climate change studies, in particular, for the early versions of the EOSDIS. The temperature and moisture sounders on the NOAA

POES are collecting the critical background information for the future EOS atmospheric profiling systems. While the measurements from geostationary and other polar orbiter spacecraft will provide a somewhat lower resolution than some research instruments selected for EOS, they will continue the long time series started in the 1970s that have provided the heritage of observations that led to the design of the EOS program and instruments. The geosynchronous spacecraft also will continue to obtain some of the essential information throughout the daily cycle. *Because global change and climate research studies all require long series of measurements, it will be important to interrelate the future space observations with earlier NOAA satellite data in order to produce long records of important variables.*

During the EOS time frame, NASA's and NOAA's existing plans would lead to a number of observational deficiencies. For studies in the atmospheric sciences, these deficiencies include (1) the inherent limitations of satellite instruments for comprehensively measuring such quantities as surface fluxes of heat, water vapor, and solar and thermal radiation, as well as distributions of surface pressure and key surface properties such as soil moisture and snow depth; (2) the absence of measurements of the three-dimensional distribution of precipitation beyond TRMM; (3) the lack of observations on a frequent basis, particularly coverage of the daily cycle with high-resolution imaging, microwave imaging, and scatterometer measurements comparable to those of EOS; and (4) the potential absence of global wind field measurements.

The first issue can be addressed by coordinated satellite, field, and modeling programs that cover those processes and their electromagnetic signatures. Important studies using currently available data have been carried out, and others are under way or in the planning stage. The International Satellite Land Surface Climatology Project is an example of a successful research program already in progress. *There will be a continuing requirement for coordinated satellite, in situ, and modeling programs as new instruments with different spatial, spectral, and signal-to-noise characteristics are flown.*

Although EOS from its polar orbit will obtain some precipitation measurements with the MIMR and MODIS instruments, there are currently no plans to obtain radar measurements or low-inclination orbital sampling of precipitation beyond TRMM. The possibility of a gap in precipitation measurements from space is critical because latent heat release due to precipitation is the single most important internal driver of the atmospheric circulation. Therefore, *there will be a need to measure precipitation on a global basis throughout the EOS time frame, and the committee considers it important for NASA to develop plans to continue such measurements in cooperation with our foreign partners in Mission to Planet Earth.*

The limited coverage of the daily cycle by EOS is particularly serious for the assessment of boundary fluxes and cloud and precipitation processes, since they vary greatly on diurnal or shorter time scales. To address this issue, *it is necessary for NASA and NOAA to continue to improve observations from geosynchronous satellites and to obtain data from complementary spacecraft flown by other countries. Full development and coordination of the NOAA polar and geosynchronous satellite programs with the EOS program are particularly important in this context, as well as for assuring long-term continuity of observations.* Current plans at NOAA call for a suite of instruments on future geosynchronous satellites that would provide an excellent complement to EOS, but it is not yet clear whether future funding levels will allow these plans to be achieved on time. Although coordination between NOAA and the outside scientific community, and between NASA and NOAA, have improved, an even stronger integration of efforts is needed.

Finally, *it is important for NASA to continue the development of an instrument that could obtain the important global wind field measurements.*

The Stratosphere and Mesosphere

Science Objectives

According to the 1985 SSB/CES report, the highest-priority objectives for the study of the stratosphere and mesosphere from space are as follows:

> 1. To measure continuously total ozone and its vertical profile over the globe with sufficient accuracy to test theoretical predictions.
> 2. To measure simultaneously the vertical profiles of atoms and radicals involved in ozone chemistry and the source and sink species of these atoms and radicals, as a function of latitude and time of year.

Current Status

One of the remarkable scientific achievements of the past decade has been the discovery of the seasonal ozone hole in the Antarctic and the rapid scientific response, including aircraft, balloon, and surface-based campaigns coordinated with space-based measurements. These observations verified that industrial chlorofluorocarbon emissions, activated by the unique meteorological conditions in the Antarctic (and, to a lesser extent, the Arctic) stratosphere, were the principal cause of the phenomenon. NASA, NOAA, NSF, and the agencies of other nations played key roles in this cooperative scientific effort. The rapid incorporation of the results of these programs into the formulation of policy responses can be attributed in part to the timeliness and quality of this research.

Following the important contributions of the Nimbus-7 Limb Infrared

Monitor of the Stratosphere (LIMS) and Pressure Modulator Radiometer (PMR) to our knowledge of the dynamical and chemical structure of the stratosphere and mesosphere, data on distributions of ozone and oxides of nitrogen were extended by measurements from the Solar Mesosphere Explorer (SME) spacecraft. Aerosol and ozone measurements were also obtained by the Stratospheric Aerosol and Gas Experiment (SAGE) mission. Currently, space-based observations of this region are limited primarily to the measurement of total ozone and vertical distribution of ozone with the Total Ozone Mapping Spectrometer (TOMS) on Nimbus-7, and the Solar Backscatter Ultraviolet (SBUV) instruments on Nimbus-7 and on the NOAA POES. These measurements, when combined with surface-based total ozone measurements, have led to new assessments for the trends in ozone levels, which have indicated that chlorofluorocarbons may be contributing to worldwide depletion, not just polar depletion, of stratospheric ozone. A follow-on TOMS is to be launched on a USSR Meteor-3 satellite during the summer of 1991 to provide continuity of the global stratospheric ozone observations.

Anticipated Improvements

The next major step forward will be the launch of the Upper Atmosphere Research Satellite (UARS) in the fall of 1991. The UARS mission will provide global measurements of a suite of trace gases and free radicals together with ozone and temperature measurements, and for the first time in the stratosphere and mesosphere, direct measurements of winds. These measurements should go far toward meeting the scientific objectives for the stratosphere and mesosphere, which are aimed largely at understanding the natural and anthropogenic mechanisms for seasonal and interannual variability and long-term trends in ozone, associated trace gases, and large-scale circulation.

Beginning with the launch of EOS-A, the High-Resolution Infrared Dynamical Limb Sounder (HIRDLS) instrument will take a further step toward meeting the objectives of the 1985 SSB/CES report by obtaining global measurements of ozone, temperature, and key trace gases with high horizontal and vertical resolution from the upper troposphere (in cloud-free regions) into the mesosphere. Additional relevant instruments currently proposed for flight on EOS-B include the Spectroscopy of the Atmosphere Using Far Infrared Emission (SAFIRE) instrument, which would make high-precision measurements of key trace species, including free radicals; the Solar Stellar Irradiance Comparison Experiment (SOLSTICE), which would monitor the critically important solar ultraviolet flux; SAGE-III, which would provide precise data on aerosols, as well as on the distributions of ozone and other trace gases; and the Stratospheric Wind Infrared Limb Sounder

(SWIRLS), which would directly measure stratospheric winds. The latter is important since geostrophic winds derivable from the temperature distribution are not accurate enough for calculation of the transport of trace species on a day-to-day basis. This suite of instruments would provide an excellent basis for long-term monitoring of ozone and the factors that control its variations.

Additional Needs

The UARS has a nominal mission life of 18 months, and although it is likely to provide measurements for a longer time, there is a need for continued monitoring of the ozone distribution in the period between the termination of UARS and the launch of EOS-A. In the meantime, measurements of total column ozone with the TOMS instrument will be continued on several spacecraft, and the SBUV instruments will be flown on the NOAA POES series. The TOMS should make it possible to continue tracking trends in total ozone, and the SBUV instruments will provide very useful information on the three-dimensional ozone distribution in the stratosphere. However, recent studies have shown that calibration drifts of the SBUV instruments can confuse the detection of trends using SBUV alone and that the previously flown SAGE instrument would provide a more reliable trend assessment. For this reason, *the committee considers it important to complement the post-UARS ozone measurement program with SAGE measurements.*

CLIMATE STUDIES

Science Objectives

The highest-priority objectives established by the 1985 SSB/CES report for the study of long-term climatic changes from space are the following:

> 1. To measure the long-term global and regional trends in external and internal climate forcings: the variables that must be measured are the solar flux, the radiative fluxes at the top of the atmosphere, radiatively important trace gases and aerosols, and certain land-surface properties (vegetative cover, soil moisture, albedo, and emissivity).
> 2. To measure the long-term global and regional changes in climate: the variables that must be measured are surface and tropospheric temperatures, precipitation, water vapor, and cloud, snow, and ice cover.

Current Status

Most of the measurements that must be made to characterize long-term global and regional trends are a subset of those required for the atmospheric science objectives discussed above. The global data sets of wind, temperature, and moisture required for studies of the troposphere, stratosphere, and mesosphere are essential for the future development of climate models, particularly for refining the parameterization of small-scale, chemical and microphysical processes required by these models.

There are, nevertheless, some special considerations for climate monitoring. These include long-term, precise, and stable measurements of atmospheric variables, such as temperature and ozone, to monitor climatic trends. Satellite passive microwave measurements have recently been shown to provide very stable temperature trend information averaged over the troposphere and lower stratosphere, while, as mentioned above, SAGE measurements, which use solar (and possible lunar) occultation techniques, can produce information on trends in stratospheric ozone and aerosols.

A critical component of climate system monitoring is the measurement of radiation balance quantities at the top of the atmosphere, including incident solar, reflected solar, and emitted thermal radiation. The contributions of the ERBE instruments to our knowledge of these variables were mentioned above. The data from ERBE, together with increased availability and usefulness of cloud information developed through the ISCCP studies, have augmented our understanding of the interactions between clouds and the top-of-the-atmosphere radiation budget parameters.

Anticipated Improvements

Precise monitoring of the solar input radiation will be extended by UARS. The CERES instrument on UARS will help to extend the observational record of the top-of-the-atmosphere radiation budget, and continued processing of historical data sets on cloud properties under the ISCCP will add to our ability to monitor the radiation budget and cloud interactions. The French-Soviet Scanner for Radiative Budget (SCARAB) mission, expected to be launched in 1992, will provide some additional data on the Earth's radiation. Other new measurements discussed in the section on the troposphere will contribute to the climate objectives as well.

Additional Needs

As mentioned above, there has been a gap in the precise measurement of reflected solar and emitted thermal radiation since the failure of the ERBE scanner. It is essential that the long-term recording of these observations be resumed as early as possible. The CERES instrument planned for TRMM would go far toward solving this problem, but would still leave a gap at high latitudes. Moreover, diurnal variations are an essential factor in measuring the radiation flux at the top of the atmosphere. For both of these reasons, *it would be desirable to place additional Earth radiation budget sensors in orbit before and during the EOS time frame, perhaps in cooperation with the space agencies of other countries.* One way of meeting these needs would be with long-term, well-calibrated measurements that could complement TRMM and EOS measurements to provide complete diurnal and latitudinal coverage of top-of-the-atmosphere radiation balance, as well as stratospheric aerosols and ozone measurements suitable for precise determination of trends in vertical profiles of ozone. *The potential seriousness of the problem of global climate change and the importance of avoiding gaps in key long-term data sets together underscore the need to ensure their continuation on a cooperative international basis.*

PHYSICAL OCEANOGRAPHY

Science Objectives

As stated in the 1982 SSB/CES report, the primary science objectives for the study of ocean dynamics from space, in order of priority, are:

1. a. To measure the time-variable sea-surface elevation;
   b. To measure the time-independent sea-surface elevation relative to the geoid;
2. To determine wind stress and its distribution over the ocean;
3. To measure directly the near-surface circulation;
4. To measure subsurface ocean properties;
5. To measure sea-surface temperatures.

The science objectives for biological oceanography are discussed later in this chapter.

Current Status

Starting with the NASA GEOS-3 and Seasat radar altimeters, and continuing more recently with the U.S. Navy's 3-year Geosat mission, the ocean science community has gathered experience in the application of satellite altimeter measurements to the study of ocean circulation variations. In many cases, the spatial coverage of the altimeter data has proved to be uniquely suited to mapping well-known but seldom observed phenomena such as oceanic Rossby waves. The lack of an accurate reference geoid (or mean gravity field on scales of a few hundred kilometers) has restricted many of these studies to oceanic variability, precluding the computation of the time-independent, sea-surface elevation relative to the geoid.

The measurement of sea-surface elevations with radar altimeters, when used with a geoid model, allows the determination of the sea surface and hence the horizontal pressure gradient. This is related to the vertical integral of the subsurface density structure. It does not, however, resolve the vertical structure within the ocean. Again, there is no deterministic connection between the vertical density distribution and the altimetric sea-surface elevation. Subsurface density measurements, when used in dynamical numerical models, provide the best means of coupling the altimetric sea-surface measurements to the internal density structure of the ocean.

The 1978 Seasat mission demonstrated that vector wind stress over the ocean could be accurately inferred by a spaceborne radar scatterometer. Improvements in antenna systems and processing algorithms have reduced the potential ambiguities in scatterometer data and made it possible to infer wind velocity from orthogonal measurements of the oceanic wind stress.

Important for the study of the air-sea heat flux is the measurement of sea-surface temperature (SST). Infrared channels on a variety of operational satellite radiometers have long been used for the routine computation of global and regional SST. Techniques have been developed for detecting and removing contamination of the SST signal by clouds and atmospheric water vapor. In addition, there is a growing realization that infrared sensors measure the outgoing radiation from the millimeter-thin skin of the ocean, and SST retrieval algorithms are being developed to account for the differences between skin and bulk SST measures at 0.5-1.0 m below the surface. This millimeter-thick skin layer is the molecular boundary between a turbulent atmosphere above and a turbulent ocean below. It is attractive to extend the computation of SST to include passive microwave measurements in order to retrieve SST in the presence of clouds. Unfortunately, past efforts with the Nimbus Scanning Multichannel Microwave Radiometer (SMMR) to compute all-weather SST were less successful than the infrared measurements, primarily due to the low spatial and radiometric resolutions.

It should be pointed out that SST is only one of the variables needed to compute the surface heat flux between atmosphere and ocean. In addition, wind speed, atmospheric temperature, cloud cover, insolation, and the water vapor pressure gradient must be known. All but the last quantity can be estimated from both present and future satellite sensors. Measurements of many of these variables are discussed in the Atmospheric Sciences section. It is important to recognize that it is the surface skin temperature, measured by the infrared satellite instruments, that is the correct SST estimate for the computation of air-sea heat flux.

Environmental satellite sensors are constrained to directly measuring only properties at or very near the sea surface and thus are incapable of directly observing any subsurface properties. Infrared instruments sample only the very thin skin of the ocean. The visible channels do integrate reflected and scattered radiation of the upper centimeter to meter of the ocean. In a non-direct measurement, the Data Collection System (DCS) on the NOAA satellites can collect and transmit data gathered by in situ buoys. Drifting buoys have been instrumented with thermistor strings to monitor the oceanic temperature profile in the upper ocean (up to 150 m) and some limited other properties. The DCS has also proved very useful for the tracking of drifting buoys as followers of ocean currents. While not a direct measurement of ocean currents, this technique based on satellite technology offers a very effective way of mapping ocean currents at the depth of the drogue element attached to the reporting buoy. In addition, the system has been effective in transferring data, such as atmospheric pressure and bulk SST. Recently, even subsurface floats have been deployed and periodically rise to the sea surface to transmit both their positions and any recorded data, such as acoustic tracking information, which can be used to plot the subsurface currents. The effectiveness of the DCS has assured its place on future satellite missions, and therefore, it can be expected to continue to be an effective method of oceanographic data collection for all future programs.

At this time it is still not possible to use imaging enhancements to directly measure surface, or near-surface currents from space. It is possible, however, to infer surface currents from the displacements of SST and ocean color patterns, as displayed in a series of sequential images. This technique is similar to the computation of winds by tracking clouds in sequential satellite images, and has been applied successfully to tracing sea ice in visible and infrared images, and SST patterns in infrared images. Preliminary approaches to this problem have been based on the use of AVHRR data.

Anticipated Improvements

Experience with the previous altimeters has demonstrated the value of satellite altimetry in being able to map the time variability of the ocean's surface and the related geostrophic ocean currents. The upcoming launch of the ESA ERS-1 mission will provide new altimeter data, although that spacecraft is not optimized for altimetry. The 1992 launch of the Ocean Topography Experiment (TOPEX/Poseidon), a joint mission between NASA and the French space agency Centre National d'Etudes Spatiales (CNES), will introduce altimeters with an advanced capability flying on a satellite dedicated to measuring and monitoring sea-surface topography and its temporal variations. In addition, the ERS-2 altimeter and a DOD-supported Geosat follow-on series could provide global altimeter coverage until the launch of the EOS Altimeter (ALT) on some component of the EOS series. There are several strong arguments for flying the EOS ALT with the Global Positioning System (GPS) Geoscience Instrument (GGI) and the Geoscience Laser Ranging System (GLRS) instruments, independent of other imaging sensors, in a non-sun-synchronous orbit.

Although NASA has experienced significant difficulties in flying a follow-on scatterometer to the Seasat mission, the committee is encouraged that the NASA Scatterometer (NSCAT) is now scheduled to fly on the Japanese ADEOS platform in 1995. The ERS-1 mission will also carry a scatterometer. The provision of a near-continuous series of oceanic wind stress maps has the potential to revolutionize the modeling and interpretation of stress-related processes taking place at the sea surface. Most important will be the actual computation of the air-sea heat and momentum exchanges that depend critically on a knowledge of the wind stress. The addition of the STIKSCAT instrument to the EOS-A spacecraft recognizes the importance of continuing the measurement of oceanic wind stress.

For the computation of SST for studies of heat exchange and ocean circulation changes associated with SST patterns, near-term plans are to continue using infrared radiometry. Improvements in atmospheric corrections will be provided by new infrared and microwave sounding instruments flying on the NOAA POES series. In the EOS time frame, plans call for SST to be computed from MODIS multichannel infrared imagery and corrected by using the microwave atmospheric sounders, AMSU-A and -B.

The large selection of spectral channels planned for the MODIS instrument also should provide even greater opportunities for inferring surface currents from sequential satellite imagery. Finally, a number of planned radar missions, discussed below, should be very useful for tracing currents and sea-ice motions under all weather conditions.

Additional Needs

A dedicated gravity mission, such as the proposed European ARISTOTELES (Applications and Research Involving Space Techniques Observing the Earth Fields from Low Earth Orbit Spacecraft), is needed to provide a high-precision, short-wavelength reference gravity field for the computation of the mean ocean circulation from satellite altimeter data. Also, the continuation of the high-precision altimeter measurements initiated by the TOPEX/Poseidon mission is required to monitor the ocean circulation and its variability.

CRYOSPHERIC RESEARCH

Science Objectives

The objectives for cryospheric research have been articulated in several documents produced by the NRC. The highest-priority objectives as summarized in the 1985 SSB/CES report are the following:

- To measure the horizontal extent, depth, density, liquid water content, and albedo of the world's snow cover.
- To measure the horizontal extent, velocity, surface temperature, albedo, and topography of the world's sea and lake ice cover and to distinguish between different ice types.
- To measure the topography of the upper and lower surfaces, thicknesses, surface areas, surface temperatures, albedo, and internal structure of the world's major glacial ice sheets and shelves.

In addition, in 1983 the Committee on Glaciology of the NRC's Polar Research Board (PRB) identified remote sensing applications in several of the overall highest priorities for snow and ice research (not ranked; PRB, 1983):

- Improved understanding of snow as an element of the global climate system through the use of remote sensing methods, field measurements to validate these, and research on snow properties that affect electromagnetic emission and scattering.
- Research on sea-ice interactions with ocean and atmosphere, using active and passive microwave remote sensing techniques to determine large-scale ice conditions (extent, concentration, and thickness).
- Emplacement of a polar-orbiting satellite carrying laser and radar altimeters for use over ice sheets.
- Continuation of ongoing field and remote sensing studies of surging glaciers.
- Continued research on remote detection of icebergs using acoustic, radar, and other instrumentation.

Current Status

An early commitment to observing the Earth's snow and ice cover from space has provided the foundation for an important global change data base. For example, significant passive microwave observations of polar ice began in the 1970s with the Nimbus SSMR and the SSM/I instrument on the DMSP. A variety of microwave, infrared, and visible data are available for studies of terrestrial snow cover.

More specifically, NASA already has established a project to assemble, from passive microwave data and other ancillary data sets, global maps of the seasonal extent of terrestrial snow cover. This project is being headed by scientists from the Goddard Space Flight Center. The USGS, NSF, and NASA all have modest surface and aircraft programs to investigate the physics of emission from snow and to provide ground truth for remote sensing data. Although geographical coverage has been good, only limited progress has been made on measuring snow pack thickness, primarily because of the complexity of separating out the effects of underlying ground and vegetative conditions from the snow signature. Finally, a major issue in the context of long-term global change research is measuring volumetric changes in the polar ice caps.

The National Aeronautics and Space Administration, NOAA, and the Office of Naval Research are sponsoring large programs to monitor the concentration, type, and dynamics of Arctic sea ice. The progress in this area is highlighted by the implementation of the Alaska SAR Facility, which will provide data for both scientific and operational activities in the Arctic, using ESA, Japanese, and Canadian SAR missions that will be launched over the next five years. A complementary program to acquire SAR data over Antarctica is currently under review by NASA and NSF. Known as the McMurdo SAR Facility, this project would provide for routine weekly observations of Antarctic sea ice and the margins of the Antarctic ice sheet in collaboration with other ground receiving stations.

An outstanding issue in sea-ice research is routine determination of ice thickness. Various methods for tackling this problem have been proposed (submarine sonar data; bottom-moored, upward-looking sonars to measure draft; low-frequency, electromagnetic systems), but none has so far proved its utility for regional, routine operations. Instead, more conventional remote sensing techniques are receiving increased attention by ice sheet glaciologists. The USGS has taken a lead role in organizing historical Landsat imagery, and NASA is compiling a mosaic of a large portion of western Antarctica. One-km-resolution AVHRR data have also been demonstrated recently to contain significant information on ice sheet dynamics. These data point to the need for redefining access by the science community to Landsat-type imagery, and to the importance of establishing archives for the 1-km AVHRR digital data.

Anticipated Improvements

The primary scientific objectives for snow and ice studies that can be addressed with EOS data later in this decade are as follows:

- To improve understanding of the influence of snow and ice on the global radiation balance, including an assessment of the importance of ice-albedo feedback as a mechanism for climate change.
- To improve our understanding of the role of snow and ice in the hydrological cycle, including fresh water supply, and in sea level change.
- To assess the role of sea-ice processes in the thermohaline circulation of the world ocean.

The first EOS spacecraft will carry the MODIS-N and -T instruments, which will be useful for snowpack monitoring. The HIRIS sensor can serve a similar purpose for more intensive mapping of limited areas. The MIMR will be useful for monitoring sea ice extent, estimating ice concentration, and distinguishing different ice types. Spacecraft in the EOS-B series are expected to carry the GLRS and ALT, which will be capable of monitoring the ice sheet topography. A long-term data base on ice sheet elevation variations has been compiled using spaceborne radar altimeter data. *To ensure continuity between the radar altimeter and the laser altimeter, the issue of whether to fly the GLRS and the ALT on the same or on separate platforms should be investigated prior to final selection of instruments for EOS-B.*

The potential contributions of the free-flying, multifrequency EOS SAR for earth studies are numerous. In the context of cryospheric research, the EOS SAR would be the best way to routinely monitor the details of sea ice cover, concentration, type, and movement, and of ice sheet dynamics. The combination of ongoing Soviet SAR observations and the European ERS-1 and -2 (1991 and 1995), the Japanese Earth Resources Satellite (JERS-1, 1992), and the Canadian Radarsat (1994) missions will provide SAR-sensing capabilities throughout most of this decade. With these systems, the pre-EOS experience should provide a better capability for utilizing EOS measurements for polar ice mapping and monitoring.

Additional Needs

Over the next several years, almost all the types of instruments identified as important for cryospheric research will be in space, albeit on separate platforms launched by different countries. Continuity of data from these instruments through the coming decades and their intercomparability will be critical in studies of the cryosphere. *Maintaining the cryospheric observations and resulting data sets, and improving our capability to interpret them will be essential in providing the heritage of experience necessary to properly use the EOS instruments and in establishing the necessary baseline for gauging global change.*

HYDROLOGY

Science Objectives

The 1985 SSB/CES report provided the following hydrology-related research objectives:

> 1. To measure the spatial distribution and amounts of [freshwater] runoff, soil moisture, precipitation, and evapotranspiration over the Earth.
> 2. To measure the various land-surface characteristics that control hydrologic responses and are affected by hydrologic change.

Current Status

The distribution of fresh surface and subsurface water is important for understanding the planetary hydrological cycle and the management of water resources. The measurement of components of the water balance, such as fresh water runoff, soil moisture, precipitation, and evapotranspiration, presents one of the most difficult challenges to satellite remote sensing. With the exception of passive microwave sensors, such as the Nimbus-7 SMMR and the DMSP SSM/I, there has been relatively little progress in defining and implementing satellite methods for the observation of these parameters. Discussion of precipitation measurements and of snow and ice cover monitoring may be found in the sections on Atmospheric Sciences and on Cryospheric Research.

With regard to the measurement of land surface characteristics that control hydrologic responses and are affected by hydrologic change, the Landsat and the French Satellite Pour l'Observation de la Terre (SPOT) series, as well as the NOAA AVHRR instrument, have provided useful data. These applications are discussed in more detail in the sections on the Troposphere, Geology, and Global Biology. The data from the Landsat and SPOT systems have not been widely used, however, because of their high cost and the continuing lack of familiarity with the use of satellite data by most hydrological researchers.

Anticipated Improvements

The extensive diurnal variability of fresh water runoff, soil moisture, precipitation, and evapotranspiration means that the EOS-A polar orbit is not well suited for their measurement. Nevertheless, a number of the EOS-A sensors should provide either direct or indirect estimates of these variables. In addition, as discussed in the Atmospheric Sciences section, the TRMM is being specifically designed to measure tropical rainfall.

In all cases the computation of these variables requires the highest possible spatial and spectral resolution. The HIRIS and Advanced Spaceborne Thermal Emission and Reflection (ASTER) instruments therefore have the potential of making the most substantial contributions to their measurement. Some limited estimates of these variables can be made with the lower spatial resolution of the MODIS sensor, but the resolution required for mapping topography for runoff, the small cells of precipitation, and the complex patterns of evapotranspiration all require the higher spatial resolutions of the HIRIS and ASTER instruments. Soil moisture and evapotranspiration particularly require the high-resolution thermal infrared measurements made by ASTER, which will also allow the estimation of the thermal inertia of individual hydrologic units.

Any estimate of precipitation, runoff, soil moisture, and evapotranspiration requires good topographic data. The EOS instruments that can provide some of this information are the GLRS and the ASTER. In addition, the ALT (sea ice), GGI, and EOS SAR can provide useful data for the computation of land-surface topography. However, the computation of a detailed global topography map with adequate spatial resolution and accuracy will require a dedicated topographic mapping mission, as discussed in the section on Geology.

Additional Needs

There is a need to better define the measurement requirements for the observation of biophysical processes as the planning for the EOS mission matures. For example, the EOS SAR could provide important measurements of soil moisture, in addition to being able to assess vegetative activity below the tree-level plant canopy. The MODIS instrument will provide estimates of vegetal condition and may also be capable of limited estimates of soil moisture from a combination of infrared channels. *The determination of the capabilities of the EOS instruments for assessing the short- and long-term balance of these quantities should be considered in planning the hydrologic research component of the EOS program and its practical applications.* For instance, short-term assessments are needed for predictions of floods and the management of irrigated agricultural lands. Long-term assessments are required for improving drought relief planning, water yield projects, irrigation or reclamation projects, and the like.

The development of two of the most useful instruments for hydrologic research, the HIRIS and EOS SAR, has unfortunately been delayed, and neither is likely to fly until after the turn of the century. The multi-frequency, multi-polarization, multi-look-angle EOS SAR in particular has the potential to provide the best assessments of biomass and soil moisture on a global basis. Finally, as noted above, few hydrologic scientists are trained in the use of satellite data for their research, despite many promising applications. The agencies involved in hydrological research should place greater emphasis on remote sensing training and education programs, and on making satellite data products available in forms that are useful to researchers who are not remote sensing experts (see *Opportunities in the Hydrologic Sciences*; WSTB, 1991).

GEOLOGY

Science Objectives

The primary science objectives for the study of continental geology from space, established in the 1982 SSB/CES report, in order of priority, are as follows:

1. To determine the global distribution and composition of continental rock units.
2. To determine the morphology and structural fabric of the Earth's land surface.
3. To measure temporal changes in geological conditions at the Earth's surface.

Current Status

The compositions of rocks indicate the sources and compositions of their parent materials and the basic processes responsible for their formation. The distribution of rock units can show the extent to which these formation and modification processes operated and the direction and magnitude of crustal deformation. Such deformation provides evidence of the kind and extent of dynamic processes in the Earth's crust.

Measurements of the land surface from space are essential for understanding the present and past development of continents. Repetitive coverage from spaceborne sensors is the best and most efficient tool for monitoring changes in geological conditions at the Earth's surface. Synoptic views can give a regional perspective of the geomorphic character of a complex and diverse terrain. Repetitive coverage by spacecraft is also important in measuring temporal changes caused by earthquakes, volcanism, and continental uplift and subsidence on a global scale.

The identification and interpretation of continental rock units from space and the mapping of their global distribution are progressing at a slow pace because of (1) the high cost of remote sensing data from the Landsat Thematic Mapper (TM) and the French SPOT [satellite] series, and (2) the general lack of availability of sensors with high spectral and spatial resolution from the visible to microwave regions. The Landsat TM, which has three visible bands and three reflected infrared bands at 28.5 × 28.5 m spatial resolution, greatly improves discrimination of rock types. The addition of the 2.1-μm to 2.5-μm band in Landsat-4 and -5 has allowed the identification of hydroxyl ions of hydrothermal alternation zones, which are associated with mineralization. Unfortunately, relatively few earth scientists are able to use the data in academic research because the costs are high. As a consequence, the existing Landsat TM data have not been used extensively to map the continental rock units over the globe.

A major application of the Thematic Mapper sensor is to map the composition of rocks and soils, and to identify geological structures and stratigraphic facies. Silicate and carbonate minerals cannot be mapped from space, however, because there is no space sensor currently available with sufficiently high spectral and spatial resolution in the thermal infrared region. *The development of instruments with an enhanced thermal infrared sensing capability would improve the mapping of rock units in the continents.*

The lower-resolution NOAA AVHRR and Landsat Multispectral Scanner (MSS) data have been used extensively to map structural patterns associated with tectonic activity and regional landforms. The main advantage of space imagery is the broad-area coverage for the geomorphic analysis of landforms, but there is a need to map globally the Earth's surficial form with better spectral and spatial resolution. Landsat TM and SPOT data can be used for mapping detailed geological structures and lithology on a global basis.

Anticipated Improvements

Improved measurements with new high-resolution sensors will enhance the regional and local studies. Microwave sensors have proven to be the most efficient tool for mapping fractures and lineaments for regional tectonic analysis in forest terrain. Radar can also help in the identification of rock types and weathering processes, and would yield information about the structural fabric of the Earth's surface and about global forest areas. Until recently, the Soviets had the only operational radar imaging capability, but as noted above, ESA is planning to launch its own radar on the ERS-1 mission in 1991, which will be followed by Japanese and Canadian missions in 1992 and 1994, respectively.

During the EOS time frame, the high spatial resolution coupled with the very large number of spectral bands of the planned HIRIS instrument would represent the next major step, as a follow-on to the Landsat and SPOT instruments, in monitoring the land surface from space. Although the 30-m spatial resolution of HIRIS would be no greater than that of instruments currently in operation, the 192 spectral bands on HIRIS would greatly improve the available spectral resolution, which would be very useful in identifying surface minerals. The ASTER instrument can be expected to yield complementary corroborative data because of its stereo imaging capability in the visible and near-infrared, and its six short wavelength infrared and five thermal channels.

The 1978 Seasat mission and the Shuttle Imaging Radars (SIRs)-A and -B have already yielded geological information about structural features in clouded and vegetated areas and about subsurface geology under very dry conditions. The SIR-C, planned for Shuttle flights in the next few years, is expected to provide new insight into the backscatter response of the Earth's surface at different radar frequencies. The advanced, cross-polarized capability planned for the EOS SAR would provide more detailed information in different terrains.

Laser ranging from space, using the GLRS instrument on EOS-B and operating it in the altimeter mode, would be capable of yielding morphological information on selected land areas and especially on ice surfaces. Using reflecting cube-corners with the GLRS would provide information on small-scale, short-time morphological change, necessary for improved understanding of the processes associated with earthquakes and volcanic eruptions.

Additional Needs

In the 1982 SSB/CES report, *the committee recommended that digital topographic data be acquired of all land surfaces as a primary means to determine the morphology and structural fabric of the continental crust.* It stipulated that spatial resolution should be 30 m or less, and that topographic heights should be measured to an accuracy of 10 m or better. The stereo-imaging capability at 10- and 20-m spatial resolution from SPOT is now providing a partial global topographic data base for structural interpretation. *The committee endorses NASA's preliminary plan to fly a topographic mission in the late 1990s and considers such a mission to be important for both geologic and hydrologic studies.*

GEODYNAMICS

Science Objectives

The primary science objectives identified in the 1982 SSB/CES report for the study of solid-earth dynamics from space, in order of priority, are as follows:

1. To measure the present rates of motion between the stable portions of the Earth's major tectonic plates.
2. To measure time-dependent deformation in a number of the major worldwide seismic zones using space techniques.
3. To measure the Earth's gravitational field from global scales to wavelengths of 200 km or less.
4. To measure variations in the Earth's rotation rate and polar motion with increased accuracy.
5. To initiate the determination of large-scale vertical and horizontal motions in the interiors of the Earth's major tectonic plates.

Current Status

According to the theory of plate tectonics, the Earth's surface is divided into a number of separate plates, moving relative to one another as approximately rigid units, and interacting mainly at their edges, causing earthquakes, volcanic activity, and a wide range of structural features, from mountain belts to ocean trenches. These plates are the cold, thermal boundary layers to the underlying convection cells in the mantle. One of the important ways in which space-based observations can contribute to geodynamics is by directly measuring the crustal motions. For example, do the plates really move as rigid objects and with constant velocities with respect to the boundaries? Is the present-day motion of the plate interiors consistent with the motion inferred over geologic time? How is the strain distributed in the region between the plate interior, where the motion is presumably steady, and the boundary, where it is usually episodic? What does the motion look like at plate boundaries, particularly before and after an earthquake? Is there evidence of sizable aseismic strain release in major fault zones? What are the rate and spatial dependence of the present-day vertical uplift due to postglacial rebound? Furthermore, estimates of vertical displacements along coastlines with millimeter-level accuracies could help remove tectonic effects from tide gauge data to better constrain the global rise in sea level. Also, precise observations of local surface subsidence could help indicate the degree of water depletion in underground reservoirs. Finally, accurate measurements of the time-varying, long-wavelength components of the Earth's gravity field, and the associated variations in the Earth's rotation are important in understanding the interactions among the atmosphere, ocean, and solid earth.

Space-geodetic techniques, including satellite laser ranging (SLR), very-long-baseline interferometry (VLBI), and radio interferometry using the GPS satellites, are beginning to answer some of these questions. Land-based techniques are competitive over distances of approximately a few tens of kilometers and especially when continual monitoring of a particular baseline is desired. Over longer baselines, however, space-based techniques are far superior.

The space-based positioning techniques (particularly VLBI, SLR, and lunar laser ranging) can also be used to infer time-dependent variations in the mantle's rotation rate and in the position of the rotation axis. Variability can be caused by the exchange of angular momentum between the mantle and the fluid regions of the Earth: the atmosphere, the oceans, and the core. These observations can be used to help constrain certain properties of the core and lower mantle, including the mantle's electrical conductivity and the shape of the core-mantle boundary. They also provide data for an independent assessment of certain atmospheric and oceanic variables, and insight into how angular momentum is exchanged between the solid earth and the atmosphere, oceans, and hydrosphere. Measurements of the time variations of the Earth's gravity field are possible by SLR to special satellites such as Lageos.

During the past decade, the NASA program has been responsive to a number of the recommendations in the 1982 and 1985 SSB/CES reports. In particular, the development of space-based techniques with the capability for measuring global tectonic motion has led to the confirmation of plate tectonics theory. The development and demonstration of the SLR and VLBI techniques for measuring plate motion and for measuring variations in the Earth's rotation rate have been major accomplishments by NASA during the

1980s. The SLR and VLBI techniques provide the capability for defining and maintaining an accurate terrestrial reference frame, which is necessary for monitoring long-term changes in global plate motions and for monitoring secular trends in ice sheet topography and mean ocean surface. These latter signals will be important in the study of global warming and will play a major role in the long-term global change research initiatives.

Anticipated Improvements

The plans during the 1990s include placing in orbit Lageos-2 and Lageos-3 as targets for further satellite laser ranging studies. These targets, along with improved ranging precision in the SLR systems, will provide high temporal resolution for a better discrimination of the time variations in both the Earth's rotation and the tectonic plate motion. In addition, the specific configuration identified for Lageos-3, which is driven by a requirement for attempting to measure the Lense-Thirring frame rotation predicted by general relativity, will be an especially important satellite configuration for measuring the tidal variation and time-dependent gravity signals, and as a means of providing a better tie to an inertial reference frame.

The full deployment of the Defense Department's GPS will provide the capability for performing low-cost, regionally dense measurements of relative position at accuracies that are consistent with the accuracy achieved by the SLR and VLBI techniques. The GPS has the potential for fulfilling the dense grid measurement requirements inherent in measuring time-dependent deformation in the major worldwide seismic zones.

The deployment of the 21-satellite GPS by the mid-1990s also will provide the potential for achieving a large number of precise measurements to support the long baseline (continental and intercontinental length) measurements by VLBI and SLR systems. If the research community can get unrestricted access to the GPS signals, the data will provide a significant improvement in the ability to rapidly produce a large number of precise regional measurements.

Some gravity data over the oceans are expected to be obtained by the ALT instrument on EOS-B. Flying the ALT in a polar orbit as currently planned, however, would not be optimal for this measurement. Although the EOS-B ALT will be a TOPEX/Poseidon-class nadir-pointing instrument, its flight in a polar orbit would not provide either a more accurate oceanic geoid or more precise measurements of ocean circulation than earlier altimeters; however, it would provide estimates along a different ground track.

Improved point positioning measurements for augmenting the GPS data are expected to be provided by the GLRS on EOS-B. The GLRS is the only instrument proposed for EOS-B that would be used primarily for geodynamic purposes, although it also would have applications for snow, ice, and cloud studies. The instrument also would complement existing VLBI, SLR, and GPS space techniques in determining plate motions and deformation. In addition, the GLRS would provide information on Earth's rotation, although it is not yet clear whether the results would be comparable in quality to the results obtained with other techniques. The GLRS would be particularly effective for monitoring areas near fault zones and volcanos, where relatively rapid deformation can be expected. Those areas would be covered with a dense array of retroreflectors, which would be sampled repeatedly by the onboard laser to detect sudden motion.

Finally, the proposed EOS Geomagnetic Observing System (GOS) instrument would be able to provide valuable information on the time dependence of the magnetic field originating in the core. The magnetometer that would be carried on the proposed ARISTOTELES mission also would be useful for determining how the magnetic field has changed since the 1979-1980 Magsat mission.

Additional Needs

The question arises as to whether some SLR and VLBI systems should be replaced by GPS systems, and if so, when. *Further validation and collocation studies are an essential prerequisite to understanding the accuracy of the GPS and to evaluating the possible problems encountered as a result of restricted access to GPS data.* At present, the SLR is the only technique with the demonstrated ability to ensure that the origin of the terrestrial reference system is coincident with the Earth's center of mass. Further, VLBI is the only technique that ties the terrestrial reference system to the quasar-based inertial reference system. Consequently, *the committee views the SLR and VLBI techniques as being crucial to the task of maintaining the reference frame required for monitoring long-term global change, and they should continue to have a significant role in the future complement of space-based geodetic techniques.* This issue is discussed in greater detail in the NRC report *International Network of Global Fiducial Stations* (BESR, 1991), which is fully consistent with the CES views.

The committee notes further that there is a continuing strong requirement for a dedicated gravity satellite, such as the Gravitational Research Mission proposed under NASA's Earth Probes program, or ESA's ARISTOTELES mission. (See also the Physical Oceanography section above.)

GLOBAL BIOLOGY, ECOLOGY, AND BIOGEOCHEMICAL CYCLES

Land-Surface Vegetation

Science Objectives

The scientific objectives identified in the 1986 SSB/CPB report for studying land-surface vegetation on a global basis are as follows:

- Measure total area covered and geographic distribution of major biomes.
- Measure the rate of change of distribution of major biomes.
- Measure biomass density for each biome.
- Vegetation production (annual):
  1. Use leaf area index as key variable relating vegetation reflectance to biomass and biological production.
  2. Test active microwave techniques to measure biomass, canopy moisture, and soil moisture.

Current Status

The understanding of the interaction between vegetation and the land surface is progressing, but at a slow pace. The land surface is very complex in its chemical, biological, and geological composition; thus, the slow rate of progress is understandable. An additional issue is the definition of the satellite capability to address these questions. The spectral and spatial resolution necessary to map globally the vegetal communities or biomes has not been addressed adequately. The NOAA AVHRR data have been used extensively to map vegetation over the globe, but the transformation of those data into physiological or biological information has not yet been accomplished.

Remote sensing technology has been used to map forest cover, areas under cultivation, and areas of deforestation. It has also been used to study causes of land degradation and eventual desertification. The technology has helped determine which areas may be brought into agricultural production and which ones are more fragile and should be kept in natural vegetation cover. However, the scientific synergism of combining remote sensing measurements from space with ground-based data has not been adequately proven globally. Physical variables such as slope, soil type, erosion, and rainfall distribution, combined with the major biomes observed from space, can more efficiently assist in monitoring land use. The United Nations Environment Program estimates that 6 million hectares of land are becoming desert each year owing to soil degradation. Multitemporal remote sensing data combined with ground-based data can be used to establish baselines of land-use patterns and to monitor seasonal changes in desert interfaces, soil moisture, vegetation, and human settlements.

The rate of change on the land surface varies. If the change is induced by human activity, such as the clearing of trees or the planting of new crops, the change can be rapid. If the change is climate-induced, the change can be slow and subtle. The spectral, temporal, and spatial resolutions required to detect vegetal changes vary with the type of disturbance or change being addressed. Tropical deforestation has been successfully studied using AVHRR and Landsat. Vegetation changes induced by climate will be detected first in the areas between ecological units, and the spectral and spatial resolution requirements could be quite different.

Anticipated Improvements

During the EOS time frame, the MODIS will provide greatly improved spectral resolution of the land surface. Studies have been and are being conducted to develop sampling strategies on selected biomes. An excellent model was provided by the work done through the International Satellite Land Surface Climatology Project in 1987 and 1989, and similar studies are being planned. Because of the investment in data collection for such large-scale field studies, it will be important to continue to support the data analysis before moving to new biomes.

New sensors with high spectral and spatial resolutions, such as HIRIS, would be useful for identifying soils and vegetation communities. Measurements from space in the thermal infrared (e.g., ASTER, MODIS) and microwave (e.g., EOS SAR) regions would also better define the surface condition and global changes of Earth.

In agricultural crops, the spectral reflectance is highly correlated to biomass and production because the plants have developed to efficiently capture light energy with their leaves. Thus there is a high correlation between leaf area and biomass over much of the growing season. However, in many other vegetation communities, such as native grasslands and forests, leaf area and biomass are not strongly correlated. Light intercepted by the vegetal canopy appears to have the potential to be directly quantified by remote sensing observations from HIRIS and MODIS. Biophysical models are then necessary to simulate net primary production.

The EOS SAR has the potential to measure global biomass and to assess surface soil moisture, but not the soil water content throughout the root zone of most plants. Surface soil moisture is useful in assessing runoff and, therefore, important in constructing the water balance. In many ecological units, soil moisture is a primary limitation to net primary production. The greatest potential for using radar backscatter information is through the use of models and their inversion to obtain canopy characteristics.

Additional Needs

Information about net primary production, biogeochemical cycling, carbon pools, and vegetal condition (e.g., physiological stress) is essential to fully assess global change. For some areas, such as wetlands, the spectral features of vegetation have a high correlation to biomass; in others, such as native grassland, the correlation is much weaker. This inconsistency among biomes is due to the complex interaction between the radiation field and the vegetal elements, as well as the background features such as soil or organic residues. It has become evident that *higher spectral resolution than that provided by the Landsat MSS or TM is necessary to reduce the background noise. In addition, the temporal resolution requirements have not been well identified for the assessment of major biomes.*

Transitions between vegetation communities, or "ecotones," can be used to study climatic changes because the plants there are at the frontier of their physiological limits and are therefore most responsive to environmental change. Ecotones are quite varied in structure and in their sensitivity to environmental change. Theory suggests that the morphology of ecotones should be useful in predicting the effects of alteration in the environment. Unfortunately, the important studies of vegetation using remotely sensed imagery have universally concentrated on general features using crude scalar analyses. Exploratory research needs to be performed that will determine the feasibility of analyzing satellite images of vegetation to locate transitions and boundaries that are especially sensitive for detecting changes in the Earth's environment. These structures are the "hot spots" at which climate- or pollution-induced change may first occur. For the study of ecotones, AVHRR and even Landsat MSS data will not have adequate spatial resolution. Spatial resolutions of 30 m or better, particularly those combined with the high spectral resolution that would be provided by an instrument such as HIRIS, will be required for this type of research as well.

Fresh Water, Wetlands, and Estuaries

Science Objectives

The 1986 SSB/CPB report established the following scientific objectives for the study of fresh water, wetlands, and estuaries from space:

- For the 20 largest rivers, determine annual rate of transport of carbon, nitrogen, sulfur, and phosphorus from land to oceans.
- Determine area covered and geographic distribution of coastal wetlands.
- Determine production of greenhouse gases from wetlands (methane and carbon dioxide).

Current Status

During the past decade, NASA has supported a series of small research projects focused on riverine systems, wetlands, and estuaries, and in 1989, NOAA initiated a broad-based Coastal Ocean Program. Both agencies have begun several research programs that are making important contributions to a better understanding of wetlands and estuaries, and their significance to global ecology.

For instance, since 1984, NASA has supported a highly focused program using satellites to measure wetland biomass production and to relate that to the emission of greenhouse gases such as methane. As a result, researchers have demonstrated that both Landsat and SPOT data can be used to provide accurately the geographic distribution of coastal wetlands. Major plant species in coastal wetlands can now be mapped with Landsat and SPOT with accuracies ranging from 80 percent to 95 percent. Biomass of *Spartina* marshes can be determined with TM and SPOT within 10 percent of ground-measured values. Remotely sensed above-ground biomass is being related to below-ground biomass production.

The Landsat MSS and TM sensors, and the SPOT sensors have good spatial resolution, but their temporal coverage is very poor and their spectral bands are not ideal for measuring concentrations of suspended or dissolved substances in the water column. Nevertheless, these sensors are suitable for mapping several suspended-sediment and flow patterns. The NOAA AVHRR sensors provide daily coverage and are quite effective for tracking the dynamics of certain phytoplankton blooms, turbidity maxima, and Gulf Stream rings, among other parameters. The AVHRR has a spatial resolution of only 1.1 km, however, and its spectral bands are not ideal for mapping sediment or chlorophyll concentration.

The Nimbus-7 Coastal Zone Color Scanner (CZCS) provided global maps of open-ocean chlorophyll between 1978 and 1986. Despite its name, however, the CZCS was not designed for near-shore coastal and estuarine remote sensing. Its sensors could not handle the wide dynamic range of radiances backscattered from turbid waters, and it had insufficient spatial resolution (0.8 km) for estuarine studies.

The National Aeronautics and Space Administration has begun a Fresh Water Initiative (FWI), a multiyear interagency program devoted to acquiring a predictive understanding of freshwater systems in the context of global change. Study areas will include freshwater ecology, hydrology, and resources. The FWI is designed to coordinate ongoing and future programs aimed at acquiring a predictive understanding of freshwater ecosystems and resources. This can be used to improve detection, assessment, and prediction of environmental effects, and develop management and mitigation alternatives for potential global change scenarios. NASA is leading the planning process, but is cooperating with 14 bureaus and services representing eight federal agencies: the departments of Energy, the Interior, Defense, and Agriculture; NOAA; NSF; the Environmental Protection Agency; and the Tennessee Valley Authority.

The National Aeronautics and Space Administration has already made substantial progress in developing satellite techniques for wetlands studies in support of the USGCRP. Similarly, NOAA's sponsorship through the Small Business Innovation Research program for small companies to develop a remote sensing instrument package for estuarine observations from small, single-engine aircraft is providing researchers with an inexpensive option for wetland and estuarine studies.

Anticipated Improvements

The committee expects that the spectral resolution of the future HIRIS instrument on EOS will enable researchers to further improve biomass and stress measurements in temperate wetlands, and to extend them to freshwater and tropical wetlands. Riverine and wetland features are frequently narrow and have complex spectral signatures. Thus high spectral and spatial resolution is required not only for studies of wetlands, but also for studies of rivers and estuaries.

Estuarine waters typically contain high concentrations of dissolved and suspended materials that arise from or have an impact on biological activity in the water. These substances may also, in some cases, be used as tracers to study circulation patterns in the estuary. Many of these materials are optically active and influence the spectral and angular distribution of the light in the water column. As a result, measurements of the detailed spectral characteristics of the light within the water column and above the surface may be used to determine the concentrations of various materials in the water. Better spectral resolution, such as that expected with HIRIS, is required to discriminate between chlorophyll, dissolved organics, suspended sediments, and other dissolved or suspended substances and to correct for atmospheric effects. Satellite sensors alone, however, cannot provide the temporal and spatial resolutions required by watershed, hydrodynamic water quality, and living resource models of estuaries. Based on requirements for spatial and temporal resolution, it is obvious that no single spacecraft can provide the necessary tidal, daily, and weekly coverage required for studies of coastal and estuarine test sites.

Aircraft can provide frequent overflights at good spatial resolution, but the large four-engine aircraft used in the past are too expensive to be flown repeatedly. A new sensor package is being developed with NOAA and NASA support, which will be small enough to fit on single- or twin-engine aircraft with a tenfold reduction in operating costs. The sensor package will include a small multispectral video camera for color measurements of the water from which chlorophyll, suspended sediment, and concentrations of dissolved organic solids can be estimated. A thermal infrared radiometer will be used to measure surface temperature, and a microwave radiometer, which is at present being reduced in size, will be used to measure water salinity. Deployed in conjunction with high-resolution satellite sensors such as HIRIS, these airborne sensors should be able to observe tidal, seasonal, and annual variations and spatial distributions of phytoplankton blooms, sediment plumes, estuarine fronts, circulation patterns, and other estuarine phenomena.

Biogeochemical Cycles

Science Objectives

The highest-priority objectives established in the 1985 SSB/CES report and the 1986 SSB/CPB report for the study of global biogeochemical cycles from space are as follows:

1. Develop computer simulation models of the biospheric cycles of carbon, nitrogen, sulfur, and phosphorus as a function of the state of the biota, climate dynamics, and interactions among these cycles.
2. To measure the concentration of chlorophyll-a in the world's oceans.
3. To measure the magnitudes of the terrestrial and oceanic sources and sinks for radiatively and chemically important tropospheric trace gases, in particular CO_2, CO, CH_4 and other hydrocarbons, N_2O, NH_3, $(CH_3)_2S$, H_2S, OCS, and SO_2.

Current Status

Work supported by NASA's Ecosystem Dynamics and Biogeochemical Cycles Branch and Biogeochemistry and Geophysics Branch, both within the Earth Science and Applications Division, specifically addresses this recommendation. These newly formed branches are focused on the following:

- Cycling of carbon and key nutrients within ecosystems, and between ecosystems and their abiotic environment;
- Identification of sources of radiatively and chemically active trace gases; and
- Quantification of major exchanges of these gases between the Earth's biosphere and its atmosphere.

Progress over the previous five years toward understanding the role of the ocean biota in global biogeochemical cycles of carbon, nitrogen, sulfur, and phosphorus has focused on efforts to quantify the effects of phytoplankton. In particular, the goal has been to study the spatial and temporal variability of phytoplankton biomass (as chlorophyll or "pigment" concentrations) and rates of primary production (carbon fixation).

The principal satellite sensor for measuring phytoplankton was the CZCS on Nimbus-7. This sensor measured upwelling radiance in six narrow spectral bands in the visible to near-infrared range. These measurements were used to derive phytoplankton concentrations expressed as chlorophyll concentration. The CZCS differed from the land-oriented multispectral imagers, such as those on Landsat or SPOT, in that it had several narrow bands in the blue-green spectral region, much coarser spatial resolution, and gains set to accommodate the relatively low radiance levels reflected from the ocean.

Because the CZCS was an experimental system, algorithms for interpreting the data evolved throughout the lifetime of the sensor. Since the end of the sensor's operational life in 1986, scientists at NASA's Goddard Space Flight Center, together with colleagues at the University of Miami, have reprocessed the entire CZCS archive to produce a self-consistent data set to be used by the oceanographic research community. These data have been distributed on optical disks to several NASA-supported facilities, which have been equipped with video disk systems for browsing the CZCS archive.

The National Aeronautics and Space Administration has also supported work aimed at understanding the production and fate of calcite (calcium carbonate) particles produced by a group of phytoplankton species known as coccolithophores. Extensive blooms of these species have been observed as bright, highly reflective patches in CZCS and AVHRR visible-channel data throughout the North Atlantic. These species may play a significant role in atmospheric sulfur cycles as they produce dimethyl sulfide, which acts as a source of sulfate aerosols in the atmosphere. It has also been hypothesized that these organisms influence cloud formation over the ocean, and hence have a potential role in the global radiation budget.

Anticipated Improvements

The ability to quantify phytoplankton pigment concentrations in surface waters does not automatically translate into carbon fixation rates. A number of investigations have been conducted to derive algorithms for estimating primary productivity or photosynthetic carbon fixation rates from remote sensing data. These algorithms will be tested in the near term using data from an ocean color instrument called the Sea Wide Field Sensor (SeaWIFS) and later from the MODIS sensors on EOS. The SeaWIFS will fly onboard the commercial Sea Star mission, scheduled for a mid-1993 launch, whereby the contractor will sell the satellite data to commercial customers. NASA has agreed in advance to purchase data for distribution to the research community.

Sensor Development for Remote Sensing of the Biosphere

The 1986 SSB/CPB report had several recommendations concerning instrumentation:

1. Develop calibrated sensors capable of high spectral resolution measurement in the 0.4-μm to 2.5-μm region.
2. Develop calibrated, active microwave sensors at wavelengths from millimeters to 1 m.
3. Develop sensors to detect emissive infrared wavelengths in the 2-μm to 5.5-μm and 10-μm to 12-μm region.

The flights of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) over the past few years have met the objective for limited areal coverage in the 0.4-μm to 2.5-μm region. The HIRIS instrument, expected to eventually fly in the EOS program, would enable critical regional process studies.

As discussed above, efforts are under way to build the SeaWIFS, which will have eight spectral bands ranging from about 400 nm to 890 nm. The additional bands will accommodate the need to differentiate substances other than phytoplankton that affect water color in near-shore regions. This addition is expected to improve our ability to study phytoplankton distributions in regions affected by terrigenous input.

There is currently no operational active microwave sensor operating at frequencies higher than about 5 GHz that is generally available to the scientific community. The successful implementation and calibration of the Jet Propulsion Laboratory's Airborne Imaging Radar provide limited areal coverage at the P-band (440 MHz, 70 cm), L-band (1.2 GHz, 25 cm), and C-band (5.3 GHz, 6 cm). The ERS-1, JERS-1, and Radarsat missions will provide valuable large-scale coverage, but they will have limited value for quantitative measurement because of their single-frequency limitation. The SIR-C, scheduled for Shuttle flights in 1993, 1994, and 1996, will provide increased polarimetric coverage at regional scales for C-band and L-band, and X-band polarized data. However, there remain concerns related to the delay in the development of the EOS SAR for global-scale coverage.

At this time there is no high-resolution infrared sensor operating in the 2-μm to 5.5-μm region that is available to the science community. Data in this region of the spectrum are expected to become available with flight of the ASTER instrument on the EOS-A satellite. Although the Thermal Infrared Multispectral Scanner (TIMS) acquires data in six channels between 8 μm and 12 μm, and ASTER will acquire data in several channels in this region, there is significant interest in higher spectral resolution measurements from both airborne and spaceborne platforms, and at the present time these are not planned.

3

Applications Programs and Other Major Issues

This chapter presents a review of the recommendations of the former Space Applications Board (SAB) of the NRC with regard to the Earth observation satellite applications programs in NASA, NOAA, and the private sector. In addition, the government's progress in key program areas—the Earth Probe small missions program, data management, research and analysis, and the relation of space, airborne, and ground measurements—is evaluated.

APPLICATIONS PROGRAMS

At the time of the SAB report *Remote Sensing of the Earth from Space: A Program in Crisis* (SAB, 1985), the operation of Landsat was being transferred to the private sector and the expectation of the government was that the Landsat program would soon become self-sustaining as a commercial operation. That "privatization" process has been widely criticized, and the prospects for the system's commercial success remain very much in doubt. The U.S. Global Change Research Program (USGCRP) also had not yet been established as the scientific and programmatic rationale for the Earth Observing System (EOS) and the Mission to Planet Earth. Those programs now provide a new context in which the earlier advice must be analyzed. A substantial number of the findings and recommendations of the 1985 SAB report have been either addressed or made obsolete because the circumstances have changed.

The following is an analysis of the findings and recommendations from the 1985 SAB report that in the view of the Committee on Earth Studies (CES) remain largely relevant.

> Recommendation II(A): Earth remote sensing should be an established and significant part of the nation's civil space enterprise.

The civil space enterprise consists of government and private-sector spacecraft conducting both routine operational and experimental research missions. Over the years, NASA has led the world in developing a broad range of instrumentation and techniques for Earth remote sensing, and NOAA has provided international leadership through its operational polar orbiting and geostationary environmental satellite programs. The Landsat program, despite significant problems encountered in its transfer to the private sector, has nonetheless provided an uninterrupted stream of data and images since 1972, which has established a unique record of the world's changing landscape.

The National Aeronautics and Space Administration is currently attempting to integrate over three decades of experience into a comprehensive observational program—Mission to Planet Earth—consisting of EOS, the Earth Probe mission line, the EOS Data and Information System (EOSDIS), and in the more distant future, geostationary platforms. NASA's initiative is coordinated with the NOAA operational programs and the Earth observation programs of many other nations. The recent top-level *Report of the Advisory Committee on the Future of the U.S. Space Program* (NASA, 1990) has supported Mission to Planet Earth as a high priority.

In short, *the committee concludes that the implementation of Mission to Planet Earth, together with the modernization of NOAA's environmental satellite programs and the continuation of vigorous research and development of remote sensing and related technologies, will ensure United States leadership in Earth remote sensing.*

> Recommendation II(B): Special attention should be devoted to improving the cost-effectiveness of the federal effort in civil remote sensing (for example, by flying both operational and research instruments on the same satellite platforms).

Some of the operational meteorological sensors from the NOAA satellites will be flown on both the EOS and European spacecraft. A European satellite series is being planned to replace one of the two NOAA polar-orbiting satellite series at the end of this decade. Further, NOAA has selected six of the research sensors scheduled for EOS as "pre-operational," for eventual transfer to operational NOAA spacecraft. These developments indicate progress toward meeting the sense of this recommendation.

> Recommendation IV(B): Operational land remote sensing for civil purposes should be accomplished in the future by a system owned and managed by the private sector (if at all feasible). At least in the early years, funding will have to come, in large part, from government.

The Landsat system was transferred to the Earth Observation Satellite (EOSAT) Company in 1985. The experience to date indicates that this transfer was premature because of the lack of a sufficiently developed commercial market for the data. Also, the transfer was poorly implemented. Under the terms of the transfer, the government agreed to subsidize the operation of Landsat-4 and -5, in addition to the procurement and launch of Landsat-6 and -7. For several years following the transfer, however, the budgets proposed by the Office of Management and Budget failed to honor the commitment. After much debate, funding was restored every year by a reluctant Congress. Funding uncertainties caused delays and cost overruns in the development of Landsat-6, postponed the development of Landsat-7, and made it more difficult for EOSAT to develop a market for Landsat data products. Also, EOSAT has charged relatively high prices for most Landsat data, with the result that the scientific community has used these data considerably less than anticipated. As a result of these and other problems, the future of this valuable remote sensing program remains uncertain. *The effective integration of the Landsat data into the research framework of the Mission to Planet Earth and U.S. Global Change Research Program is especially important.*

> FINDING VII. From a purely technical point of view, the partition of the civil Earth remote sensing program into private- and public-sector components and into operations and research is an unnecessary complication that has thus far only added to the cost and difficulty of creating and maintaining a successful operational program. In an Earth-viewing system that uses space platforms and other hardware with a maximum degree of cost-effectiveness, each satellite could carry land, atmosphere, and ocean sensors, and each could carry operational and experimental sensors. Observational and orbital requirements, not institutional or programmatic labels, would determine on what satellite a given sensor was flown.

The separation of Earth observation activities into research, operational, and commercial categories has often led to significant duplications of effort, and contradictory data policies. The interagency CEES coordination activities appear to be reducing a number of the inconsistencies in the policies under which the nation's civil remote sensing programs are operated, particularly with regard to the availability of data from government agencies. Full coordination among federal agency, commercial, and foreign Earth observation programs remains elusive, however, and it is unclear whether the Mission to Planet Earth can be operated with maximum efficiency under existing government procurement and commercial remote sensing policies.

> FINDING VIII. The volume of data flow in civil Earth remote sensing is growing rapidly and will eventually exceed 10^{13} bits per day. Data processing, evaluation, analysis, dissemination, and archiving are be-

> coming more difficult and costly. A substantial effort is needed to plan and operate the required data-handling systems.

(This finding is discussed under the Data Management section later in this chapter.)

> Recommendation IX(A): NOAA (in cooperation with NASA) should develop a long-range plan for the federal role in operational Earth remote sensing. To the maximum degree possible, this plan should facilitate common use of spacecraft and data-handling systems by institutions (public and private) that mount Earth remote sensing programs. To help control costs, the number of special-purpose satellites must be held to a minimum.

The coordination between NASA's EOS and NOAA's POES system has made a significant step in this direction and incorporates many of the principles given in this finding. Although substantial portions of the EOS program, especially the ground segments, are benefitting from the coordinated effort, a comprehensive long-range plan between NASA and NOAA has not yet been developed.

Significant problems remain, in particular, in NOAA's development of the next-generation GOES system in conjunction with NASA and its contractors. The new GOES system has had severe cost overruns and schedule delays, and one of the two remaining GOES has experienced on-orbit failure. As a result, the nation is at risk of losing all of its synoptic meteorological observations and the linchpin of its severe weather warning capability prior to the completion and launch of the new GOES system, now scheduled for the fall of 1992. In this regard, the committee would like to underscore the recommendations for increasing the POES and GOES R&D funding that were made in the *Report of the Advisory Committee on the Future of the U.S. Space Program* (NASA, 1990).

The Earth Probe line plus possible special-orbit satellites in the EOS program, such as the advanced SAR, make up the set of special-purpose satellites referred to in recommendation IX(A). Contrary to the advice of the SAB, the CES considers these special-purpose spacecraft to be an essential component of Mission to Planet Earth and the USGCRP. The scientific rationale for such missions was reviewed in detail in the committee's report *Strategy for Earth Explorers in Global Earth Sciences* (SSB, 1988), which is discussed in the next section, Earth Probe Mission Line.

> Recommendation IX(B): The system plan should center around the needs of operational programs . . . Whenever possible, space should be made available for research sensors on vehicles that are used primarily for operational purposes. The potentialities of the Earth orbiting platforms (to be launched as part of the space station program) should be fully exploited. The polar orbiting space platform is especially important for Earth remote sensing.

With the exception of space for research sensors on the NOAA satellites, this recommendation appears to have been followed well by NASA in the EOS program and with its international collaborators. The EOS-A orbit is similar to the orbit of the NOAA POES, but the "platform" is no longer a part of the Space Station program. The committee agrees with the SAB that the polar-orbiting EOS spacecraft are "especially important" for Earth remote sensing. The recommendation that NOAA make space available for research sensors remains appropriate. In fact, some limited space on NOAA satellites is available, at least for small instruments on an occasional basis. A recent example was the flight of the ERBE scanner on the NOAA POES.

> Recommendation IX(C): The present effort to encourage increased multinational cooperation in the Earth remote sensing program is promising and should be continued and expanded. This will promote international good will and will further help to limit national expenditures.

International collaboration related to the NASA and NOAA Earth observation satellite programs has provided progress in this direction through joint program planning, exchange of instruments, and mutual access to data. Although there have already been substantial cost savings through international cooperation in the programs of both agencies, current plans call for NASA's and NOAA's foreign partners to fund an even greater share of the joint programs. For example, the European Meteorological Satellite (EUMETSAT) organization is expected to assume the responsibility in the late 1990s for building and operating one of the two POES currently operated by NOAA, and several nations are planning to contribute instruments to the EOS program. The USGCRP, which has been developed since this recommendation was drafted, has generally justified increased expenditures for remote sensing by all of the cooperating nations.

It is important to emphasize that a number of other nations now have significant technological capabilities for conducting Earth observations from space. Many of the proposed sensors on the planned satellite missions of various nations have very similar measurement capabilities in terms of their spectral and spatial resolution. While such overlapping capabilities provide a hedge against the loss of our ability to acquire specific types of data in the event of the failure of an individual sensor system, and are essential for observing important phenomena with diurnal variations, excessive redundancy in sensor characteristics is inefficient.

In light of limited federal budgetary resources, the committee considers it important for NASA, in collaboration with the scientific community and its interagency and international partners, to develop an integrated, global observational strategy and an equitable and appropriate division of labor that maximizes observational coverage by (1) eliminating observational gaps *in coverage of the electromagnetic spectrum and (2) reducing redundancies, with the exception of those redundancies that help maintain continuity of key measurements and that provide multiple observations of variables, such as those related to clouds, energy budgets, and vegetation, which require measurements throughout the day. Both the development and implementation of this comprehensive observational strategy should be done in concert with the independent scientific community.* For additional discussion of the importance of developing such an observational strategy, see NRC (1990).

> Recommendation X(A): NASA should launch and operate the space platforms and design and manage the downlinks to be developed as part of the space station program. Operational Earth remote sensors (NOAA and commercial) should be given high priority on the polar orbiting platform. NASA should also develop station tending and repair capabilities for space platforms and retrieval capabilities for other Earth-orbiting satellites (including those in geostationary orbit). NASA should develop new sensors for operations, in consultation with NOAA and other users, and should carry out basic space-oriented R&D on the physics and chemistry of atmosphere, ocean, and land systems.

With the exception of the Space Station servicing scheme, the spirit of this recommendation is well reflected in the planned programs. The Earth Observing System is no longer linked to the Space Station program, primarily because the EOS spacecraft cannot be serviced either from the proposed Space Station or from the Shuttle. The committee considers this decoupling from the Space Station program to have been a positive step for the implementation of the research objectives.

The operational sensors for NOAA satellites generally have been given high priority, although, as mentioned above, the development of the next generation of GOES sensors and spacecraft has encountered serious difficulties. Also, Landsat is still not well integrated into these plans.

A number of instruments developed by NASA in the past, such as the Earth Radiation Budget Experiment (ERBE) scanner, the Coastal Zone Color Scanner (CZCS), and the Total Ozone Mapping Spectrometer (TOMS), have not been transferred to NOAA for operational status despite the demonstrated maturity of the technology and the well-recognized need for such continuous measurements. Although NASA and NOAA have reached a tentative agreement on the designation of several EOS instruments as "pre-operational," the framework of the eventual transfer has not been worked out, and the agencies have not yet agreed on the future status of the important MODIS instrument. *Past difficulties in transferring well-tested experimental instruments to operational status underscores the imperative for the federal government to arrive at a firm and comprehensive agreement on*

NASA's and NOAA's responsibilities and funding for the eventual transfer of key EOS instruments to a long-term monitoring program.

The National Aeronautics and Space Administration is carrying out its responsibilities in the research areas listed in the recommendation, as well as in other areas. The Earth Observing System is the "centerpiece" of the USGCRP and has been assessed in the report of the Committee on Global Change (NRC, 1990) and in the "Space Studies Board Position on the NASA Earth Observing System" (SSB, 1991) as generally meeting the established scientific priorities.

> Recommendation X(B): NOAA should build and (under contract with NASA) launch operational satellites or lease space on commercial spacecraft. It should own and manage the atmosphere-ocean operational observing system and provide federal oversight (and, as appropriate, initial federal subsidy) for the commercially operated land remote sensing system. NOAA should carry out research on application of space-derived information, should be responsible for archiving all Earth remote sensing data, and should disseminate atmosphere and ocean data to the user community.

The National Oceanic and Atmospheric Administration is performing many of these functions, in principle, although the agency has not received funding adequate to support ocean remote sensing on an operational basis. The selection of several EOS ocean remote sensing instruments for pre-operational status, however, has been an important step in this direction. Responsibility for archiving remote sensing data in support of global change research is shared by NASA, NOAA, and USGS.

At the time this recommendation was drafted, the SAB was reviewing the roles and missions of NASA and NOAA, and the division of responsibilities between the federal agencies and the commercial sector. These institutional aspects considered by the SAB have been largely overtaken by events, notably by the interagency approach to a nationally and internationally integrated Mission to Planet Earth. The SAB's attempt to assign roles among the various remote sensing satellite operators therefore needs to be reassessed in the new context; however, such an analysis is beyond the scope of this report.

> Recommendation X(C): The commercial sector should own and manage the operational land remote sensing system, purchasing space when appropriate on NASA and NOAA satellites. It should build new operational sensors and should fly its own satellites as it deems necessary (leasing space when appropriate to NOAA or NASA). The commercial sector should also be responsible for marketing space-derived land remote sensing data to the various user communities, including government departments such as Agriculture and the Interior.

As has already been pointed out, this process was initiated with the

Landsat program, and it has not been satisfactory. The USGCRP provides a new imperative that all data that can be used in such research be widely available, inexpensive, and easy to access. Consistent with the recommendations of the 1990 NRC report, several aspects of the Landsat legislation should be reexamined and changed to facilitate access to the Landsat data for scientific researchers and to lift restrictions on NASA in the release of EOS data.

> Recommendation XVIII(A): Programs to support academic research facilities, student training, and scientist visits and exchanges should be increased. The timely flow to research institutions of data from both operational and research and development satellites should be assured.

This recommendation remains relevant and important. The substantial increase in engineering and science activities related to satellite remote sensing has already exceeded the capacity of existing educational programs. Although there is a recognition of this problem in the EOS program (i.e., 0.25 percent of the EOS budget has been devoted to educational fellowships), concerns remain as to whether this program alone can produce a sufficient number of new remote sensing experts to fully exploit the research and applications potential of the many planned missions. The National Oceanic and Atmospheric Administration established several new university research centers in the 1980s, some of which are focusing on remote sensing applications. *A rigorous review of the existing and projected skilled personnel base in relation to the requirements identified for the Mission to Planet Earth program and the USGCRP by the principal agencies funding those programs would be especially useful.*

In addition, it is important to note that NASA has no formal procedure in place for adding new investigators to the EOS program. *It is essential for NASA to develop a mechanism for bringing new co-investigators and guest investigators into the EOS program over the program's lifetime, and to adequately support research opportunities outside the Principal Investigator program, including those related to remote sensing engineering.*

> Recommendation XVIII(B): Research scientists at the universities and in government should be consulted with regard to the design of (and plans to improve) operational satellite systems. These systems provide information necessary to advance basic science.

This recommendation has not been implemented. In a briefing by NOAA officials, the Committee on Earth Studies was informed that the specifications for the next set of operational instruments for the NOAA polar orbiters were established internally by NOAA through consultations with its line organizations. No direct attempt was made to obtain operational and research requirements from user groups outside the agency. Research scientists at universities and in government can provide valuable advice. *The* *establishment of a formal process at NOAA for consulting with knowledgeable individuals outside the agency, as well as with major user groups, would help ensure maximum utility of the data collected by its satellites.*

> Recommendation XIX: Further development of a value-added industry that uses (or enhances) and markets remotely sensed data should be encouraged. A necessary requirement is a federal commitment to the continuity and timely dissemination of satellite observations.

The federal government devotes little attention to developing commercial remote sensing applications. Despite the fact that many instruments in Mission to Planet Earth will provide information potentially useful for a broad range of socioeconomic applications, both the research programs and data-dissemination plans at NASA generally do not support the development of those applications. The primary emphasis is on climatology, long-term global change, and ecology—with the latter ignoring the impact on ecology of the large fraction of land area covered with crops and urban development. Although NOAA and the commercial sector have primary responsibility for operational remote sensing, *NASA has a mandate for supporting research in and development of broad remote sensing applications. It is important for the agency to incorporate potential applications of the EOS system into its planning for the program, while preserving the primacy of the EOS program's scientific goals and objectives. These activities would best be coordinated with industry and with the commercial and government applications communities.*

The committee believes that NASA's plans for Mission to Planet Earth, together with the operational environmental satellite observations of NOAA and the satellite programs of other nations, could adequately fulfill the general requirement for continuity of observations. Nevertheless, the agencies still need to develop a comprehensive strategy with appropriate contingency planning, in addition to full instrument calibration and data validation for intercomparison of observations from different sensors over the long term.

As the various Earth observation programs progress, NASA, NOAA, and their foreign space agency partners should preserve long-term continuity and intercomparability of measurements in the process of upgrading instruments and responding to evolving research priorities. *In particular, the committee considers it vital that the agencies mount a special effort to ensure the continuous absolute calibration and intercalibration of all EOS instruments and the instruments of other related national and foreign Earth observation spacecraft to the highest achievable accuracy. It is also important for NASA to continue to formulate a backup strategy and policy to be implemented in case of an instrument failure. This strategy may consist of the generation of alternative geophysical parameters, albeit less effective* *ones, from either complementary EOS instruments or from sensors flying on other NASA, U.S., or foreign spacecraft. The backup strategy ought to aim for the smoothest possible transition from the full complement of EOS sensors to the backup geophysical parameters calculated in case of primary sensor failure(s).*

Concerning the timely dissemination of the data, the committee finds the data distribution plans in the EOS program to be responsive to the requirements of the scientific research community. The data distribution policies for the broader applications and commercial sectors, however, need to be reviewed.

EARTH PROBE MISSION LINE

Summary of Recommendations

The report *Strategy for Earth Explorers in Global Earth Sciences* (SSB, 1988) provided the scientific rationale and strategy for a line of small- to moderate-size research satellites within NASA's Earth Science and Applications Division. The principal recommendations in that report were as follows:

> *The Committee on Earth Sciences recommends that a new Earth Explorer mission series be funded at a level that would allow the construction of two small missions per year, or one moderate mission every 3 years. Announcements of opportunity for such missions should be divided according to two separate solicitations, one for missions and instruments costing less than $30 million and one for missions in the $30 million to $150 million range.*
>
> The traditional strength of the existing NASA Explorer line has been easy, frequent, and inexpensive access to space. The recommendations that follow are designed to return similar opportunities to the earth sciences.
>
> 1. *Each Earth Explorer mission should be sharply focused on significant scientific issues.* A mission should explore important scientific issues or fill in gaps that may arise in the collection of long-term data sets. The program could also provide the collateral benefit of advancing technology development in achieving its objectives. In any case, the missions should be justified by their own scientific merit. The Earth Explorers should not be used for the engineering development and flight testing of instruments for large missions or platforms.
> 2. *Programmatic continuity and flexibility must be maintained.* In order for the recommended program to have a significant impact on the earth sciences, it must be started with a clear expectation of maintaining uninterrupted continuity. The program should also be designed for flexibility, both in choosing the most important scientific questions to

address and in allowing for reasonably wide variations in the scale of the missions. Rapid response times are necessary to react in a timely manner to sudden changes in our environment, or to take advantage of opportunities to collaborate with other agencies.

3. *Costs must be rigorously controlled in all phases of the program.* The key to the success of the Earth Explorer program will be to obtain the maximum scientific value per dollar expended. The spiraling costs of instruments for observations from space can be controlled by sharply focusing the scientific objectives, by assigning principal investigators the prime responsibility for quality and cost control, and by carefully assessing the tradeoff between reliability and multiple copies of instruments. Standard satellite buses and launch vehicles should be used whenever this is both scientifically and economically advantageous.

4. Given the emphasis on strongly focused missions, the data transmission and processing activities are likely to be relatively modest. Nevertheless, *strict schedules and reliability requirements must be met, and the data should be made available as quickly as possible to scientific archives or to open networks in scientific formats. Careful planning and experimentation with the integration over networks of data from diverse sources will be essential.*

5. *A significant fraction of the total costs for each mission should be allocated to data analysis, interpretation, and related theoretical modeling work.* Because the scientific objectives for any mission are achieved only after the data have been distributed and thoroughly analyzed, adequate funding for this purpose is fundamental to the mission's success. The committee strongly recommends that the appropriate resource levels be allocated to the mission operations and data analysis budget to support such activities.

6. *A basic goal of the Earth Explorer program must be to speed up the conversion of concepts into satellite missions and of raw data into scientific results.* The time scales of the program must be designed to attract leading scientists and talented students, and to avoid the mounting costs of protracted space projects. Therefore it is essential that the missions be launched within 2 to 3 years of acceptance of engineering design for the smallest missions, and 3 to 4 years for the moderate-size ones.

7. *The Earth Explorer program must develop a selection process that encourages the best ideas and does not require inordinate investments in engineering design during the initial proposal phase.* To achieve this objective the selection process should proceed in two phases. In the first phase, proposals should be requested that emphasize the scientific issues and the instrument concepts, with only a limited discussion of engineering issues. In the second phase, only the most promising concepts should be chosen for further development and preliminary instrument design in order to compete in a further selection process. This approach will minimize the total community investment in preparing proposals, and will make it attractive for scientists with good ideas but

limited resources to compete in the preliminary phase of Earth Explorer selection. The over selection of missions or instruments should be assiduously avoided.

8. *Interagency and international collaboration must be optimized.* Collaboration with other agencies and nations fosters the development of a stronger space science program at reduced cost to NASA. Every opportunity for cooperation in utilizing and financing Earth Explorer missions should be considered.

Current Status

Significant opportunities exist for gathering key global change data through missions flown under an Earth Explorer line, which NASA has named the Earth Probe series. Because Earth Probes are intended to be smaller satellites with relatively short development times, they can advance the time in which some of the measurements critical to understanding global change could be made. An important concern in the near term is the interruption of key measurements, such as global stratospheric ozone levels, the Earth's radiation budget, and the biological productivity of the oceans, made by satellite missions launched in the 1980s. The Earth Probe line provides an opportunity for extending those measurements until acquisition of the data sets is resumed by the EOS spacecraft. The Earth Probes can also provide global information on a discrete set of variables or phenomena not fully measured by a dedicated mission before, such as the gravity and magnetic fields, and the topography of the land surface.

Some measurements—for instance, biological processes and radiation studies related to cloud motion—require sampling at various times of the day, and they cannot be made from sun-synchronous, polar-orbiting spacecraft such as EOS. To the extent that these measurements are critical to achieving the objectives of global change research, the Earth Probe line can provide a flexible mechanism for such observations from more appropriate orbits or for measurements that require unique orbits. During the EOS era, Earth Probe missions will also be essential for complementing the EOS measurements by flying instruments that may be incompatible with the design and orbit of the EOS platforms. It is expected that the Earth Probes will be augmented by foreign spacecraft, some of which will provide flight opportunities for U.S. instruments.

The National Aeronautics and Space Administration's response to the committee's 1988 recommendations, while not yet fully developed, has been positive. Following incremental increases in the FY 1990 and 1991 budgets, NASA's proposed budget for FY 1992 includes over $70 million for the Earth Probe line and related activities. If approved by Congress, these funds would be used to support the development and launch of four very small and two somewhat larger instruments or missions. A concomitant increase for the subsequent analysis of the data from these missions will also need to be made.

The very small missions include the separate flights of three TOMS, which will continue the historic stratospheric ozone measurements made by the TOMS on Nimbus-7. The first of these follow-on missions will place a TOMS on the Soviet Meteor-3 weather satellite, currently scheduled for launch in August 1991. The second TOMS would be launched on a small dedicated spacecraft in 1993, and the third on the Japanese ADEOS mission in 1995. Later in the decade, the ozone monitoring functions are expected to be performed by the NOAA POES and the NASA EOS. The other very small mission involves the purchase of ocean color data from the commercial remote sensing mission, SeaWIFS, that is expected to be launched in 1993. This will reestablish the important global observations of the ocean's biological cycles that were begun by the Coastal Zone Color Scanner on the Nimbus-7 satellite in the early 1980s (see the discussion on ocean color measurements in the previous chapter's Global Biology section).

Two larger missions are also being developed. These are a scatterometer instrument, which will be flown on the ADEOS mission, and the Tropical Rainfall Monitoring Mission (TRMM), which is being pursued as a joint program with Japan and is also scheduled for a 1995 launch.

Anticipated Improvements and Additional Needs

Missions under active consideration by NASA for the second half of the decade would provide measurements of the Earth's gravity and magnetic fields, topography, and radiation balance. The importance of these missions is discussed in Chapter 2 and in *Strategy for Earth Explorers in Global Earth Sciences* (SSB, 1988). *The committee endorses the vigorous program already under way as well as the Earth radiation, gravity, magnetic field, and topography missions that are being considered.* Finally, *the committee considers it important that NASA request proposals from the scientific community for future Earth Probe missions through the customary open solicitation process.*

DATA MANAGEMENT

In the past, data management and related support for data analysis have been the Achilles' heel of Earth observation satellite programs. During the 1980s, a number of influential reports recommended a broad set of improvements in the way in which NASA and NOAA manage their data. Below are key recommendations excerpted from several NRC reports that the committee considers particularly relevant to the management and use of data in Earth observation research programs.

Summary of Recommendations

The following advice appeared in the report *Data Management and Computation, Volume 1: Issues and Recommendations* (SSB, 1982b), which was written by the SSB Committee on Data Management and Computation (CODMAC):

> Scientific Involvement. There should be active involvement of scientists from inception to completion of space missions, projects, and programs in order to assure production of, and access to, high-quality data sets. Scientists should be involved in planning, acquisition, processing, and archiving of data. Such involvement will maximize the science return on both science-oriented and applications-oriented missions and improve the quality of applications data for application users.
>
> Scientific Oversight. Oversight of scientific data-management activities should be implemented through a peer-review process that involves the user community.
>
> Data Availability. Data should be made available to the scientific user community in a manner suited to scientific research needs . . . .
>
> Data System Funding. Adequate financial resources should be set aside early in each project to complete data-base management and computation activities; these resources should be clearly protected from loss due to overruns in costs in other parts of a given project.

The 1985 CES report (SSB, 1985) endorsed the CODMAC (SSB, 1982b) recommendations and added the following:

> In particular, the committee recommends that an earth science information system be developed through appropriate interagency and international cooperation. This information system should consider three classes of data and the problems associated with the collection and management of each: data that already exist in archives, data to be acquired from future operational satellites, and data to be gained from future research missions.
>
> The committee also recommends that the existing satellite data be archived in a form convenient for outside users, and that proper attention be given to documenting, storing and distributing these reduced data sets.

Finally, the 1985 SAB report included the following finding:

> Finding VIII: The volume of data flow in civil Earth remote sensing is growing rapidly and will eventually exceed 10^{13} bits per day. Data processing, evaluation, analysis, dissemination, and archiving are becoming more difficult and costly. A substantial effort is needed to plan and operate the required data-handling systems.

Current Status

The National Aeronautics and Space Administration has made a great deal of progress in improving and developing new data management systems. Central data cataloging and archiving facilities have been established at the National Space Science Data Center (NSSDC) of the Goddard Space Flight Center. An on-line master directory of space and earth science data, which will be accessible worldwide, is being developed at NSSDC. This master directory will provide scientists with summary information on NASA's data holdings, and will point users to catalogs and archives where more detailed data-set information can be found and where data can be browsed or extracted. Some earth science data sets reside in the NSSDC central archive; other data reside in distributed archives located at other NASA centers and universities. These distributed archives are mission- or discipline-oriented and include the Upper Atmospheric Research Pilot Data System, Crustal Dynamics Project Data System, SAR Data Catalog System, NASA Ocean Data System, Pilot Climate Data System, and Pilot Land Data System.

Anticipated Improvements and Additional Needs

Although NASA has made significant improvements in existing information systems and data bases in recent years, the EOS program, Mission to Planet Earth, and USGCRP will require an effort that is several orders of magnitude greater. Much to the agency's credit, the EOS program places great emphasis on its Data and Information System. The EOSDIS is planned to acquire a comprehensive, global, 15-year data set; to maximize the utility of this data set for scientific purposes; and to facilitate its easy access by the research community. It is expected to be implemented as a distributed, interactive, and evolutionary data system to handle both historical and newly collected EOS data.

The EOSDIS is proposed to begin with seven existing data centers, called Distributed Active Archive Centers (DAACs), which will include the participation of scientists in their operation and are expected to emphasize science users' needs. The DAACs will be linked to other operational data centers, such as those currently operated by NOAA, the Department of Energy, and the Environmental Protection Agency. Starting with version 0, which will begin operating in 1994, the EOSDIS will archive, manage, and distribute satellite and related in situ data sets. Critical developments for the success of the EOSDIS are the ability to "browse" the DAAC data holdings and to have the requested data delivered online or offline. Catalogs, directories, and other data management functions will be performed at each of the DAACs. In addition to the data management capabilities, the later version-1 EOSDIS will include the ability to schedule and operate the EOS instruments and payloads.

The committee considers this high emphasis placed by NASA on the EOSDIS to be appropriate. The creation of the EOSDIS Science Advisory Panel was an important step forward in the development of the data system. It has already contributed to a major revision of EOSDIS, away from the centralized design that was originally proposed. The CES supports the recommendations of that advisory panel, which were strongly influenced by the 1982 CODMAC report, for a distributed system that encourages user input, provides higher-level, user-defined products, and seeks to unify software and data delivery systems. There is a serious concern, however, that these important features will not be implemented in the final design phase after award of the contract to help ensure that the system will meet the needs of the research community. These issues should remain at the forefront of attention, both within NASA and in its advisory groups. (See also, *The U.S. Global Change Research Program: An Assessment of the FY 1991 Plans*; NRC, 1990.)

It is important to note that progress in the management of Earth observation satellite data and related in situ data is being made across the federal agencies, including NOAA. Comprehensive data policies and programs are being developed by the interagency Committee on Earth and Environmental Sciences (CEES) and by the Interagency Working Group on Data Management for Global Change in the context of the USGCRP. According to the CEES budget report, *Our Changing Planet: The FY 1992 U.S. Global Change Research Program* (CEES, 1991), the focus is on an "early and continuing agency commitment to the production and preservation of high-quality, long-term data sets, data exchange standards, data access, and maintaining the lowest possible cost of data for research purposes." (p. 67)

Evidence of this cooperation is the early "Pathfinder" data sets being created for the EOSDIS. These data sets are based in part on select historical data sets from NOAA satellites and are processed by NASA onto longer-lasting storage media for copy and distribution by the version-0 DAACs. This Pathfinder activity is a critical component of the new NOAA data management initiative that is part of the NOAA Global and Climate Change Program. New data sets obtained in the early 1990s, such as those collected by the ERS-1, UARS, and TOPEX/Poseidon missions, need to be used to develop a baseline for the operational characteristics of the initial version of EOSDIS. The ERS-1 data are particularly important because they provide a comprehensive set of microwave and optical measurements collected by a foreign space agency, which will help to establish the ground rules for the international exchange of satellite data in support of the Mission to Planet Earth and the USGCRP. *It is important for NASA to continue to develop existing pathfinder data sets and to include the data sets that will be col-*

lected by ERS-1, UARS, and TOPEX/Poseidon for prototype studies in developing the EOSDIS.

Despite the significant progress made by the agencies in their management of Earth observation satellite data, a number of concerns remain. Recent reports by the General Accounting Office (*Space Operations—NASA Is Not Archiving All Potentially Valuable Data*, GAO, November 1990; and *Environmental Data—Major Effort Is Needed to Improve NOAA's Data Management and Archiving*, GAO, November 1990) have documented some serious deficiencies in the archiving of historical research satellite data by NASA, of GOES and POES data by NOAA, and of Landsat data by USGS. Some of the data sets from individual sensors, particularly the oldest ones, are in jeopardy of being irretrievably lost due to the degradation of storage media and substandard archival facilities. *Although all three agencies have begun to address these problems, it is vital that they continue to emphasize those activities necessary to rescue and properly maintain historical data sets.*

RESEARCH AND ANALYSIS

The 1982 SSB/CES report stated that:

> Vigorous support of theoretical and laboratory investigations should be an essential component of the future program for earth science from space.

Over the past 10 years, the annual budget for research and analysis (R&A) programs at the NASA Earth Science and Applications Division has been consistently well supported. In the future, interdisciplinary modeling will play a larger role in assimilating the results of process studies and laboratory investigations. As expenditures for flight hardware increase with the implementation of EOS and other flight projects in the Mission to Planet Earth, pressures will likely build to sacrifice R&A funds to meet hardware budget deficiencies, or other contingencies. *The National Aeronautics and Space Administration management should continue to work together with other agencies in the CEES and with the research community to assure that the R&A programs, so vital to the success of the USGCRP, remain vigorously supported.*

RELATION OF SPACE, AIRBORNE, AND GROUND MEASUREMENTS

The 1982 SSB/CES report urged that:

> On both scientific and strategic grounds, a coordination of space, airborne, and ground measurements and an integration of the results from

> all types of experiments should be indispensable aspects of a global program of earth science. We recommend that sufficient planning and resources be devoted to ensure that the ground and airborne measurements necessary to accomplish this strategy can be conducted in the next decade.

This recommendation is even more compelling in the context of today's interdisciplinary and international global change research. The responsibility for making ground-based and in situ observations is spread among numerous agencies in the United States and in many other nations worldwide. In conducting this review, the committee found that the plans for these types of observations, which are now being coordinated nationally through the interagency CEES, are not yet as coherent as those for spaceborne observations.

In conjunction with the other agencies involved in global change research, it is important for NASA and NOAA to continue to develop a comprehensive plan for the surface and in situ data-gathering technologies and programs that are needed to complement Earth observations from space. The NASA aircraft and suborbital programs are essential elements of this plan.

This issue of conducting a balanced observational program was included in a broader context of maintaining an "appropriate balance" within the USGCRP in the report *The U.S. Global Change Research Program: An Assessment of the FY 1991 Plans* (NRC, 1990). It defines appropriate balance as "one in which resources are allocated to the program components in a manner that will best achieve overall program goals." It goes on to evaluate balance in six contexts: between long-term and short-term investments; between extramural and agency-based research; between "big" and "little" science; among observations, process studies, and modeling; between established and emerging programs; and among science priorities. The committee agrees with the conclusions and recommendations reached on these six areas in that report.

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Abbreviations and Acronyms

ADEOS	Advanced Earth Observing Satellite
AIRS	Atmospheric Infrared Sounder
ALT	Altimeter
AMSU	Advanced Microwave Sounding Unit
ARISTOTELES	Applications and Research Involving Space Techniques Observing the Earth Fields from Low Earth Orbit Spacecraft
ASTER	Advanced Spaceborne Thermal Emission and Reflection
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
CEES	Committee on Earth and Environmental Sciences
CERES	Clouds and the Earth's Radiant Energy System
CES	Committee on Earth Studies
CNES	Centre National d'Etudes Spatiales
CODMAC	Committee on Data Management and Computation
CPB	Committee on Planetary Biology
CZCS	Coastal Zone Color Scanner
DAAC	Distributed Active Archive Center
DCS	Data Collection System
DMSP	Defense Meteorological Satellite Program
EOS	Earth Observing System
EOSAT	Earth Observation Satellite (Company)
EOSDIS	EOS Data and Information System
EOSP	Earth Observing Scanning Polarimeter
ERBE	Earth Radiation Budget Experiment
ERS-1	Earth Remote-Sensing Satellite

ESA	European Space Agency
ESAD	Earth Science and Applications Division
EUMETSAT	European Meteorological Satellite (Organization)
FWI	Fresh Water Initiative
GAO	General Accounting Office
GEOS	Geodetic Explorer
GGI	GPS Geoscience Instrument
GLRS	Geoscience Laser Ranging System
GOES	Geostationary Operational Environmental Satellite
GOS	Geomagnetic Observing System
GPS	Global Positioning System
HIRDLS	High-Resolution Infrared Dynamical Limb Sounder
HIRIS	High-Resolution Imaging Spectrometer
ICSU	International Council of Scientific Unions
IGBP	International Geosphere-Biosphere Program
ISCCP	International Satellite Cloud Climatology Project
JERS	Japanese Earth Resources Satellite
LAWS	Laser Atmospheric Wind Sounder
LIMS	Limb Infrared Monitor of the Stratosphere
MIMR	Multifrequency Imaging Microwave Radiometer
MODIS	Moderate-Resolution Imaging Spectrometer
MSS	Multispectral Scanner
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSCAT	NASA Scatterometer
NSF	National Science Foundation
NSSDC	National Space Science Data Center
OSSA	Office of Space Science and Applications
PMR	Pressure Modulator Radiometer
POES	Polar-Orbiting Operational Environmental Satellite
PRB	Polar Research Board
R&A	Research and analysis
SAB	Space Applications Board
SAFIRE	Spectroscopy of the Atmosphere Using Far Infrared Emission (instrument)
SAGE	Stratospheric Aerosol and Gas Experiment
SAR	Synthetic Aperture Radar
SBUV	Solar Backscatter Ultraviolet (instrument)
SCARAB	French-Soviet Scanner for Radiative Budget
SeaWIFS	Sea Wide Field Sensor
SIR	Shuttle Imaging Radar
SLR	Satellite Laser Ranging

SME	Solar Mesosphere Explorer
SMMR	Scanning Multichannel Microwave Radiometer
SOLSTICE	Solar Stellar Irradiance Comparison Experiment
SPOT	Satellite Pour l'Observation de la Terre
SSB	Space Studies Board
SSM/I	Special Sensor Microwave Imager
SST	Sea-surface temperature
STIKSCAT	Stick Scatterometer
SWIRLS	Stratospheric Wind Infrared Limb Sounder
TIMS	Thermal Infrared Multispectral Scanner
TM	Thematic Mapper
TOMS	Total Ozone Mapping Spectrometer
TOPEX	Ocean Topography Experiment
TOVS	TIROS Operational Vertical Sounder
TRMM	Tropical Rainfall Measurement Mission
UARS	Upper Atmosphere Research Satellite
USGCRP	U.S. Global Change Research Program
USGS	United States Geological Survey
VAS	VISSR Atmospheric Sounder
VISSR	Visible and Infrared Spin-Scan Radiometer
VLBI	Very-long-baseline interferometry
WCRP	World Climate Research Program

Appendix

Guidelines for Assessment Reports for Standing Committees of the Space Studies Board

So that the Space Studies Board (SSB) can have an ongoing assessment of the status of space science and applications research recommended in its various reports, each of the standing committees (Space Biology and Medicine, Space Astronomy and Astrophysics, Solar and Space Physics, Planetary and Lunar Exploration, Microgravity Research, and Earth Studies) is requested to provide an assessment of the way in which recommendations in the existing strategy and other reports are being implemented by the appropriate federal agencies. This assessment will be conducted every three years beginning in 1990-1991. In the interim years, the committee chairpersons will provide a formal assessment report to the SSB only. The form of report presentation, written or oral, is at the discretion of the committee. Should the SSB determine that the reports' contents or format needs to be changed, the SSB will provide the committees with the necessary guidelines to make the appropriate modifications.

A secondary objective of these assessments is for the committees to examine their existing strategies to determine if any changes are necessary and to evaluate the time scale on which the strategies need to be updated. This report is to be submitted to the SSB for review no later than March 31 of the pertinent year. Its length should be determined by the committee based on its individual needs. Each report should include an executive summary, not to exceed 15 pages.

The audience for these reports is NASA, the space research community, Congress, and relevant Executive Branch offices such as the Office of Science and Technology Policy, the Office of Management and Budget, and the National Space Council.

These reports will be published separately, as they become available. In addition, the SSB may choose to summarize and compile all of the reports into a single volume providing an overall assessment of the state of space research on a regular basis.

Each report should contain, at a minimum, the following features:

I. Introduction
   A. Description of principal areas/disciplines within committee's purview.
   B. Listing of principal SSB reports pertaining to the respective disciplines (should include title, name of authoring committee, date of publication). SSB or committee letter reports that contain information relevant to issues examined in the annual report should also be included. [In some cases, there may be non-SSB NRC reports for which the committee has oversight responsibility. In these cases, they too should be listed.] This listing may be attached as an appendix.
   C. Identification of principal users/implementors of existing reports (within NASA).
   D. Identification of potential users/implementors of existing reports (outside of NASA).

II. Status of the Discipline
   A. Discussion of *major* scientific goals/objectives in existing reports, and description of progress to date in achieving these goals/objectives.

      "Progress" includes any activity specifically pertaining to major scientific objectives, i.e., inclusion in a strategic plan, Announcements of Opportunity, cooperative agreements, budget line-items, inclusion on STS/ELV flight manifest, Phase A, B, etc., studies.
   B. Identification of *major* scientific goals/objectives in existing reports in which *no* progress (see above) has been made.

      This discussion should include the committee's assessment of why no progress has been made in addressing scientific goals/objectives (e.g., budget constraints, lack of flight opportunities, technology limitations, instrument/facility availability, management/policy decisions, and so on). It should also address, if applicable, where these goals or objectives fall in the committee's overall priorities for the discipline as a whole.

      If relevant or possible, the committee should include some guidance or recommendations for achieving these goals and objectives.

For example, the committee might recommend how relevant federal agencies (other than NASA) could address these goals and objectives under existing programs, how interagency and/or international cooperative agreements might be exploited, and so on.

C. Identification and discussion of major policy and program issues raised in existing reports and the U.S. government's and/or NASA's response.

III. Conclusions

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